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State of Practice for Emerging Waste Conversion Technologies

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State of Practice for Emerging Waste Conversion Technologies

Final Project Report

Prepared for

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Office of Research and Development
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Contents

Abbreviations and Acronyms List

AD	Anaerobic Digestion
BOD	Biological Oxygen Demand
BTU	British Thermal Unit
C&D	Construction and Demolition
COD	Chemical Oxygen Demand
CRV	Carbon Recovery Vessel
CT	Conversion Technology
D/F	Dioxins and Furans
DOE	Department of Energy
DST	Decision Support Tool
ECY WA	Department of Ecology Washington
EIA	Environmental Impact Analysis
EIS	Environmental Impact Statement
EOG	Envion Oil Generator
EPA	Environmental Protection Agency
EPIC	Environment and Plastics Industry Council
FGD	Flue Gas Desulfurization
FEMP	Federal Energy Management Program
GHG	Greenhouse Gas
HAP	Hazardous Air Pollutant
HDPE	High Density Polyethylene
HRSG	Heat Recovery Steam Generator
ICE	Internal Combustion Engine
ICI	Industrial Commercial and Institutional
ISO	International Organization for Standardization
KWh	Kilowatt hour
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LDPE	Low Density Polyethylene
LHV	Lower Heating Value
MMBtu	Millions of British Thermal Units (BTUs)
MBtu	Thousands of British Thermal Units (BTUs)
MRF	Materials Recycling Facility
MSW	Municipal Solid Waste
MW	Megawatt
MWh	Megawatt hour
NA	Not Applicable
NGO	Nongovernmental Organization
OARDC	Ohio State University's Agricultural Research and Development Center
PAC	Powered Activated Carbon
PET	Polyethylene Terephthalate
PM	Particulate Matter
P2O	Plastic2Oil
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
RDF	Refuse Derived Fuel
Syngas	Synthetic gas or Synthesis gas
TCE	Tons of Carbon Equivalent
TNMOC	Total Nonmethane Organic Carbon
TPD	Tons per Day
USDA	U.S. Department of Agriculture
VE	Visible Emissions
VOC	Volatile Organic Compound

Disclaimer

This report includes a summary of available data and information for emerging waste conversion technologies in North America. The U.S. EPA does not advocate or endorse any particular technology or facility included in this report. The analysis and report were developed from January 2011 to June 2012. Information and data were collected from interviews with technology vendors, independent engineering analyses, vendor product information and presentations, and literature/website reviews. The viability of available information or data cannot be independently verified due to the lack of performance data or independent testing being conducted to confirm vendor claims. Another difficulty in conducting a review of emerging technologies for converting waste to fuels or energy is the dynamic nature of emerging waste conversion technologies and markets.

Executive Summary

RTI International (RTI) was contracted by the U.S. Environmental Protection Agency (EPA), Office of Research and Development to conduct research to prepare a "State of Practice" report to support State and local decision-makers on the subject of emerging waste conversion technologies. Emerging technologies are defined as those in a commercial or advanced pre-commercial development stage. While the application of these technologies to municipal solid waste (MSW) feedstocks is only emerging in the United States (U.S.), these technologies have been applied for the management of MSW in other parts of the world, such as Australia, Canada, Europe, and Japan. A key aspect of international applications is that they are part of waste systems with advanced segregation, such as source segregated organics collection. Where conversion technologies have been most successful is in locations with already established programs for waste segregation and collection, dedicated waste streams (e.g., plastic from industrial partners), and waste supply contracts so that potential plants can operate economically.

For this study, focus was placed on the ability of these technologies to manage the currently non-recycled fraction of municipal solid waste (MSW) in the U.S. The specific objectives for this study and report were to develop:

- An overview of each waste conversion technology, identifying the types of feedstock that have or can be used in each process and the air, water, and waste emissions.
- Information on energy and mass balance for each technology.
- Information on the economics of the technologies to help decision-makers understand the key cost factors and economic feasibility.
- A listing and maps of proposed and operational facilities in the United States and pertinent examples for each technology.
- A summary of key findings and considerations decision-makers should be aware of when evaluating waste conversion technologies.

To address these objectives, RTI built upon research for plastics waste conversion technologies conducted for the American Chemistry Council (see RTI, 2012). In that research, pyrolysis and gasification technology vendors were identified and asked to provide process, environmental, and cost information. Additionally, publicly available data sources were retrieved to complement the data received from each vendor. This study for the EPA is specific to technologies for non-recycled MSW and includes the additional technology category of anaerobic digestion. In addition, data and information originally collected for technology vendors as part of the 2012 study for the American Chemistry Council was updated in June 2012.

Technology Types

The technologies researched are identified in **Table ES-1** along with information on the feedstock, end products, conversion efficiency, and facility capacity. Different vendors and facilities can have specific variations on the technology to enhance conversion efficiency and/or tailor the end product to site-specific markets. The primary objective of the conversion technologies is to convert waste into useful energy products that can include synthetic or synthesis gas (syngas), biogas, petroleum, and/or commodity chemicals.

Table ES-1. Overview of Conversion Technology Characteristics.[1]

Conversion Technologies	Pyrolysis	Gasification	Anaerobic Digestion
Feedstock	Plastics	MSW[2]	Food, yard, and paper wastes
Primary End Product(s)	Synthetic Oil, Petroleum Wax	Syngas, Electricity, Ethanol	Biogas, Electricity
Conversion Efficiency[1]	62–85%	69–82%	60–75%
Facility Size (Capacity)	10–30 tons per day	75–330[3] tons per day	10–100[5] tons per day
Product Energy Value	15,000–19,050 BTU/lb	11,500[4]-18,800 BTU/lb	6,000–7,000[5] BTU/lb (estimated)

[1] Conversion efficiency is defined as the percentage of feedstock energy value (e.g., btu/lb) that is transformed to and contained in the end product (e.g., syngas, oil, biogas).
[2] Only certain MSW fractions can be input to a gasifier. Glass, metals, aggregate, and other inerts are not desirable and may cause damage to the reactor.
[3] Total capacity permitted based on vendor communications. Geoplasma's St. Lucie, FL plasma gasification plant is permitted up to 686 tons/day, but the vendor could not be reached for confirmation. [Note: as of September 2012, the St. Lucie facility is no longer in development]
[4] LHV of ethanol.
[5] Estimated. AD facilities can span a wide range of sizes, input feedstocks, and designs.

The review of publicly available data and information revealed that most facilities reported to be operating as commercial-scale are often operating in more of a demonstration mode and do not have waste contracts and/or energy or product contracts in place. Because most facilities are demonstration-stage plants, they are operating in batch-test rather than in a continuous-mode that would be typical of commercial plants. Until there are commercially operating facilities in North America, there will be a high level of uncertainty in the data to characterize the performance, cost, and environmental aspects for these technologies.

Performance Summary

It is difficult to directly compare the cost and performance of pyrolysis, gasification, and AD technologies directly due to differences in feedstocks and primary products (See **Table ES-1**). Pyrolysis technologies typically process only plastics; gasification technologies typically process plastics and biodegradable fractions of MSW but avoid inerts (e.g., glass, metals, aggregate); and AD typically processes highly putrescible fractions of food, yard, and paper wastes. The difference in suitable feedstocks creates differences in feedstock energy values as well as in product energy value and related beneficial offsets. For pyrolysis, beneficial offsets are primarily based on the conversion of plastics to oil. For gasification, beneficial offsets include energy production and can also include recyclables (e.g., metals, glass, and other inorganics)

[1] Plasma arc treatment and hydrolysis technologies are not included in this table. There is only one hydrolysis facility and no plasma arc facilities in North America processing MSW and conversion technologies appear to be moving in the direction of AD, gasification, and pyrolysis.

removed in the up-front sorting process. This component, however, was not included in the analysis since we assumed post-recycling MSW would be the input feedstock and any additional recovery of recyclables would be minimal. For AD, the benefit offsets are primarily based on the conversion of organic wastes to biogas, which is assumed to be used to produce electrical energy.

Based on the available data[2], life cycle environmental assessments constructed for pyrolysis and gasification technologies were updated in 2012 by RTI. In addition, a comparable life cycle environmental assessment for AD technology was constructed for this study. Because most conversion technologies focus on feedstocks that are not suitable for conventional recycling, comparisons were made only to landfills and waste-to-energy (WTE). Based on the assessments and information gathered for conversion technologies, a qualitative evaluation was performed as shown in **Table ES-2**. As shown in Table ES-2, conversion technologies may offer environmental benefits as compared to landfill disposal. However, a clear environmental benefit as compared to conventional WTE is more difficult to discern. Similar to landfills, WTE can accept waste as is, are considered proven technologies, and can have large capacities. Conversion technologies generally have smaller capacities and are more limited in the types of materials that can be accepted. However, while the main product of WTE is electrical energy (and possibly steam), conversion technologies produce synthetic or bio-based fuels that can be either combusted to produce electrical energy, used as a transportation fuel , or sold as a chemical commodity product based on regional markets.

Table ES-2. Evaluation of Conversion Technologies.

	Landfill Diversion	Net Energy Recovery	GHG Emissions Reduction	Commodity Products Potential	Ability to Accept Bulk MSW As Is	Commercial Readiness	Cost
Pyrolysis	+ [1]	+++ [2]	+	+++	-	+	+
Gasification	++ [1]	++ [2]	++	+ [3, 4]	+	+	?
Anaerobic Digestion	+ [1]	+ [2]	++	+ [3]	-	+	?
Landfill	-	+ [2]	-	na	+++	+++	+++
WTE	+++	+++[2]	++	+	+++	+++	+

-Worse, + Good, ++ Better, +++ Best, ? Indeterminate/not enough data, na Not applicable

[1]Relatively small facility capacity, may not significantly impact landfill diversion unless there are many facilities. For example, pyrolysis accepts mainly plastic and AD mainly food and green waste.

[2] Energy recovery creates beneficial offset of utility sector electricity production or petroleum fuel production.

[3] May not be available markets or significant enough quantity to lead to marketable products.

[4] Potential glass and metals recovery and associated recycling offsets (would only apply if the facility accepts bulk MSW).

[2] The data used for this assessment were provided by industry vendors and were not independently validated. In addition, the datasets used to characterize the technologies vary in the level of detail and the number of values obtained for particular input parameters, with only one value obtained for certain parameters.

As shown in **Table ES-2**, all conversion technologies can support landfill diversion and the exact facility capacity and number of facilities will govern the significance of the diverted amount. At present, none of the technologies can directly accept MSW, except for conventional WTE. Rather, most conversion technologies can only utilize specific fractions of MSW (e.g., plastics, organics) and thus must be paired with source segregation and separate collection or robust materials separation up-front of the conversion process. This would require additional cost, energy, and use of processes with additional environmental emissions. So for location specific analysis, one most consider existing infrastructure and needs for enhanced segregation of suitable materials and contractual arrangements for ensuring dedicated feedstocks.

From an environmental perspective, the conversion technologies showed potential benefits, including reduced energy and carbon emissions. When compared to landfill disposal, gasification of 100 tons of MSW per day and operating 300 days of the year may save energy equivalent to the needs of about 1800-3600 households, or about 1500-3000 household transportation energy needs according to EPA information[3] about average household and household transportation energy needs. This translates into a reduction of approximately 33,000-66,000 tons of carbon dioxide (CO_2) per year. Pyrolysis of 100 tons per day of non-recycled plastics may save the amount of energy equivalent to the needs of about 550-1100 households, or about 460-910 household transportation energy needs and about 16,500-27,500 tons of CO_2 emissions reduction per year. Treatment of 100 tons of organics waste in an AD facility may save the amount of energy equivalent to the needs of about 170-690 households, or about 140-570 household transportation energy needs and approximately 12,000-14,000 tons of CO_2 emissions reduction per year.

Cost information for conversion technologies is limited and what is available from the literature indicates that the net cost/ton for pyrolysis is comparable to landfilling, whereas the net cost/ton for gasification and AD is higher. The estimated waste processing cost for pyrolysis is approximately $50/ton of plastics, close to $90/ton of MSW for gasification, and close to $115/ton of organics for AD. This cost is generally related to the capital and operating costs required to run the process and dispose of any residuals. For comparison, U.S. landfill tipping fees range from $15–96/ton of MSW, depending on the State or region, and average $44/ton for the entire U.S. (Van Haaren et al., 2010). WTE tipping fees range from $25–98/ton of MSW, depending on the State or region, and average $68/ton (Van Haaren et al., 2010).

Future Outlook

While conversion technologies present another option for managing non-recycled MSW, it will be an estimated 5–10 years before the first-generation demonstration facilities transition to stand-alone commercial operations (i.e., stand-alone operating facility not supported by Federal grant funding or private capital investment capital) based on estimated times for siting, permitting, construction, and contract development.

For the current suite of conversion technologies currently under development, plastics-to-oil pyrolysis technologies are more mature than MSW and organics-based technologies (typically gasification and AD), in part because of the decreased variability of the incoming feedstock—

[3] http://www.epa.gov/dced/location_efficiency_BTU-chtl-graph.htm

e.g., three facilities at a commercial stage were identified for plastics-to-oil pyrolysis, while none at a commercial stage were identified for gasification and AD.

The capability of conversion technologies to meet landfill diversion and/or energy production goals will likely depend heavily on the success of these first-generation facilities. Until these facilities are operating commercially in North America, there will not be enough real-world data to accurately characterize their environmental aspects and costs. While operating facilities exist in Europe and Asia, they are often in unique settings. For example, a cursory review of facilities in Europe indicated that they are typically located in regions where there is more separation of recovered materials, which would help with the economics as well as the operation of the conversion technology. In addition, facilities in other countries are not subject to the same State and local permitting and regulatory processes as in the U.S. Thus, they may not provide comparable data to accurately characterize environmental aspects or costs. In addition, waste sorting in Europe is much more prevalent that in the U.S. which reduces the front end costs of conversion technologies by not incurring additional costs associated with targeting specific materials.

Section 1: Introduction

New technologies to convert municipal and other waste streams into fuels and chemical commodities, termed conversion technologies, are rapidly developing. Conversion technologies are garnering increasing interest and demand due primarily to alternative energy initiatives. These technologies have the potential to serve multiple functions, such as diverting waste from landfills, reducing dependence on fossil fuels, and lowering the environmental footprint for waste management. Conversion technologies are particularly difficult to define because their market is in development and many of their design and operational features are not openly communicated by vendors.

RTI was contracted by EPA's Office of Research and Development to conduct research to evaluate and develop a "State of Practice" report for State and local decision-makers on the suite of emerging waste conversion technologies in the United States. The technologies information was collected throughout the 2011 time period and includes the general categories of pyrolysis, gasification, and AD.

The objectives for this report were to develop:

- An overview of each waste conversion technology, including identifying the types of feedstock that have or can be used in each process and the claimed and/or reported air, water, and waste emissions.
- Information on energy and mass balance for each technology.
- Information on the economics of the technologies to help decision-makers understand the key cost factors and economic feasibility.
- A listing and maps of proposed and operational facilities in the U.S. and pertinent examples for each technology.
- A summary of key findings and considerations decision-makers should be aware of when evaluating waste conversion technologies.

To address these objectives, this study evaluated real-world case examples and data and information from the literature. This analysis provides a better understanding of the range of emerging conversion technologies available that accept MSW or specific MSW fractions as primary feedstock and identifies and profiles specific technology vendors. The study was also designed to identify and quantify the potential cost and life cycle environmental burdens/benefits of the technologies as compared to existing landfill disposal. Technology categories are described in detail and potential benefits and impediments are reviewed. Additionally, an LCA was performed for the general technology categories using data from technology vendors in combination with data obtained from the literature.

1.1 Conversion Technology Development Stages

There are a number of ongoing efforts in North America to develop and commercialize waste conversion technologies. The current situation is very dynamic, with new technology proposals, new vendors, mergers and acquisitions, and redesigns or closings occurring almost weekly. It is useful to consider the technology development stages as illustrated in **Figure 1-1** when discussing waste conversion technologies. There are technologies at every stage of the

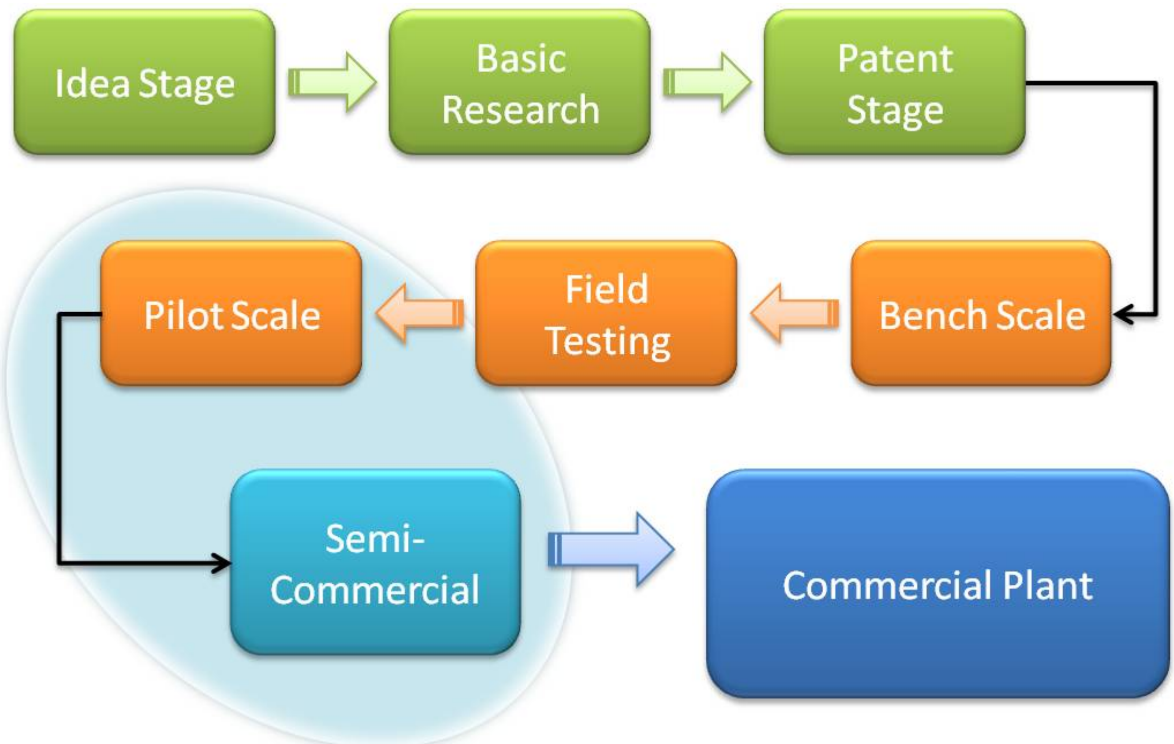

Figure 1-1. Stages of Waste Conversion Technology Development.

Note: Most of the facilities investigated in this report are in the stages within the shaded area.

development cycle. At the time the facilities specific data used in this report were collected (2011), there were only a few commercial-scale facilities operating.

Most facilities are at a pilot or semi-commercial stage. It was found that even facilities that are commercial-scale are often operating in more of a demonstration mode and most do not have waste contracts and/or energy or product contracts in place.

This study focused on technology vendors and facilities that were at the pilot to commercial plant stages. **Figure 1-2** illustrates the locations of existing North American waste conversion facilities by main technology category of AD, concentrated acid hydrolysis, gasification, and pyrolysis. Gasification and pyrolysis are the primary technology categories that can accept MSW (or MSW fractions), whereas AD and concentrated acid hydrolysis primarily accept organics. The current stages of technology development for pyrolysis, gasification, and AD facilities are discussed in **Sections 2-4**, respectively.

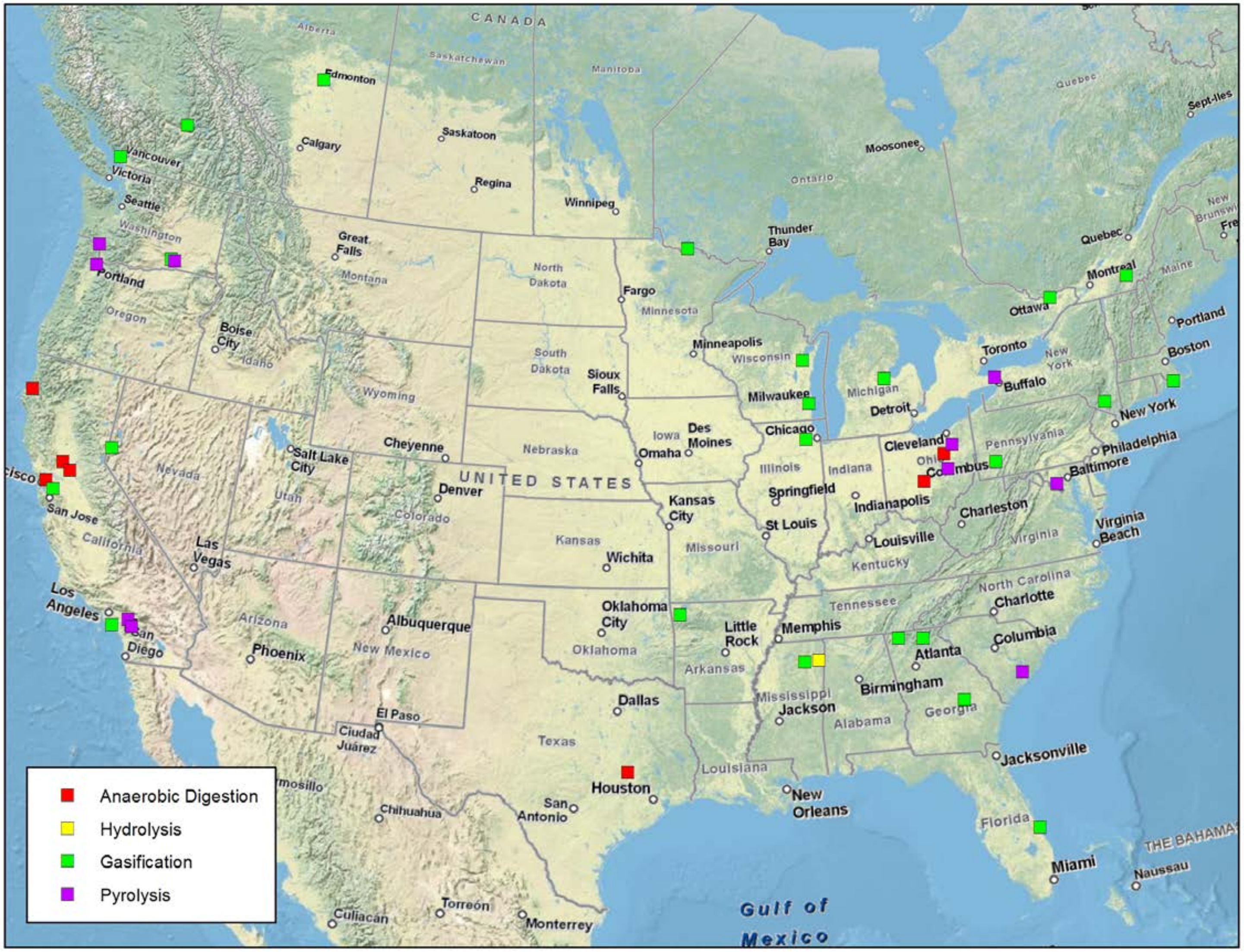

Figure 1-2. Waste Conversion Facility Types and Locations in North America (as of June 2012).

Concentrated acid hydrolysis and plasma arc technology (direct plasma treatment as opposed to plasma as part of gasification) were not included for further consideration in this report. There is only one hydrolysis facility and no plasma arc facilities in North America processing MSW and conversion technologies appear to be moving in the direction of AD, gasification, and pyrolysis.

1.2 Conversion Technology Definitions

In this report, thermal and biochemical conversion technologies are described as pyrolysis, gasification, or AD. Thermal conversion processes are characterized by higher temperatures and conversion rates than biochemical processes. These technologies contain a continuum of processes ranging from thermal decomposition in a primarily oxygen starved environment (commonly referred to as pyrolysis/cracking processes) to partial oxidation in a sub-stoichiometric environment (or gasification processes).

The definitions adopted in this report may not necessarily be the same as elsewhere or how individual technology vendors categorize their process. Our main goal was to develop general definition that would have value and meaning to State and local decision makers. With that in mind, definitions for the technologies were constructed based on the strict engineering definitions as well as the key accepted waste inputs and key outputs from the technologies.

It should be noted that vendor technologies are often difficult to fit under one technology category and sometimes include characteristics common to more than one technology. For example, in a two-stage (pyrolysis-gasification) fixed bed gasification process, some of the oxygen injected into the system is used in reactions that produce heat, so that pyrolysis (endothermic) gasification reactions can initiate, after which the exothermic reactions control and cause the gasification process to be self-sustaining.

As described in **Sections 2-3** thermal conversion processes such as pyrolysis and gasification are characterized by higher temperatures and conversion rates than biochemical processes such as AD as described in **Section 4**. As part of recent research for the American Chemistry Council (RTI, 2012), RTI designed a questionnaire to collect life cycle energy and emissions data and sent it to six facilities—Agilyx, Envion, Climax, JBI, Enerkem, and Ze-Gen. The data and information collected from these questionnaires was supplemented with additional publicly available data for each of these, and additional (e.g., AD), vendors. The data and information from this American Chemistry Council project was updated for this project to capture the current status and performance of facilities.

Since there were so few true commercial facilities in operation, it was difficult to present reliable estimates for cost and life cycle environmental aspects. Most of the facilities covered in this report were still in pilot and demonstration stages. As facilities transition to fully operational commercial facilities, one would expect the process inputs/outputs to stabilize and cost and environmental aspects to become more consistent and reliable. Given the emerging nature of these technologies and the likelihood that most data corresponds to testing under controlled batch tests, the uncertainty associated with the data should be considered high.

Table 1-2. Overview of Conversion Technology Characteristics.

Conversion Technologies	Pyrolysis	Gasification	Anaerobic Digestion
Feedstock	Plastics	MSW[2]	Food/yard wastes
Primary End Product(s)	Synthetic Oil, Petroleum Wax	Syngas, Electricity, Ethanol	Biogas, Electricity
Conversion Efficiency[1]	62–85%	69–82%	60–75%
Facility Size (Capacity)	10–30 tons per day	75–330[3] tons per day	10–100[5] tons per day
Product Energy Value	15,000–19,050 BTU/lb	11,500[4]-18,800 BTU/lb	6,000–7,000[5] BTU/lb (estimated)

[1] Conversion efficiency is defined as the percentage of feedstock energy value (e.g., btu/lb) that is extracted and contained in the end product (e.g., syngas, oil, biogas).
[2] Only certain MSW fractions can be input to a gasifier. Glass, metals, aggregate, and other inerts are not desirable and may cause damage to the reactor.
[3] Total capacity permitted based on vendor communications. Geoplasma's St. Lucie, FL plasma gasification plant is permitted up to 686 tons/day, but the vendor could not be reached for confirmation. [Note: as of September 2012, the St. Lucie facility is no longer in development]
[4] LHV of ethanol.
[5] Estimated. AD facilities can span a wide range of sizes, input feedstocks, and designs.

Any data provided by the vendors have not been independently verified. While RTI vetted data and information collected and contacted vendors for clarification where needed, very little information was obtained about the tests and test conditions used to obtain the data. Gathering this type of information, as well as performing an independent verification, is part of the recommendations from this report.

1.3 Challenges for Implementing Conversion Technologies

As with any process, the operator must obtain appropriate federal, state, and local permits. Several vendors noted difficulties with the state and local government permitting process mainly because there aren't comparable facilities to draw a precedent from and it's not always clear whether a conversion technology falls under the category of waste management or renewable energy facility. Another key difference is that there is not long-term performance data from conversion type facilities on which to establish regulatory limits and determine potential impacts on local or regional air sheds.

The permitting process can take time and the facility owners may have difficulties that lead to substantial delays in construction. Several vendors noted that they had encountered their permits rejected several times. As with any new facility, construction operations may not begin until permits are acquired. It may be necessary to obtain solid waste handling permits through the appropriate local agency. It is also important for facilities to apply for and acquire air permits in order to address any criteria pollutants and toxic air pollutants that may be emitted. One such permit would be a Title V Permit, which sanctions construction of permitted emissions units as well as initial operations (FL DEP, 2011). Emissions from startup, shutdown, and malfunction operations are also specified in air permits. Water quality permits are necessary to regulate discharges to surface and ground water. The local or county planning agency likely has requirements for the planned facility that encompass building, grading, water system, shoreline, utility, site plan review, septic system, floodplain development, and any zoning variance (ECY WA, 2011).

Before a facility is built, it may be necessary for an Environmental Impact Assessment (EIA) to be prepared. The EIA is a comprehensive evaluation of the positive and negative impacts that the proposed facility may have on the natural environment, as well as social and economic consequences. After the assessment is completed, it is likely that an environmental impact statement (EIS) will need to be written. An EIS is a decision-making tool that is required for proposed projects that may significantly impact the environment. Included in this statement is a discussion of the purpose and need for the project, alternatives, and environmental effects of the proposed project.

After firms receive permits to operate, they must be able to secure contracts with waste facilities in order to have a secure, continuous feedstock. Feedstocks are often one of the most challenging aspects of successfully operating a conversion facility. The quantity of feedstock needs to be relatively constant because the systems are optimized for a specific flow rate. It is also necessary for quality and volume of feedstock to be taken into account. Brightstar Environmental is an example of one company that encountered issues with feedstock supply. Brightstar was a subsidiary of Energy Developments Limited and located in Australia’s New South Wales province in the city of Wollongong. The gasification facility was forced to close in 2004 due to feedstock contractual issues.

Most revenue from these processes comes from the sale of oil, gas, and/or electricity. Therefore, if markets are not developed for recycled products from the pre-sorting process, revenue that otherwise would have been generated is lost. Furthermore, if no market share exists and clients are not found for the oil or gas products, the facilities will be forced to close due to a lack of revenue.

Ash and other residual products from waste conversion technologies can be a regulated hazardous waste or solid waste and will need to be assessed and approved by local or state agencies to determine their potential use (e.g., as aggregate) and appropriate disposal (e.g., conventional versus hazardous waste landfill). Slag that may be produced is characterized by technology vendors as non-leachable. However, it may require testing for compliance with state and local regulations or standards and will likely need to be approved for reuse applications. If a market is developed for slag and it is approved for reuse, it may be sold. If not, the slag must be landfilled.

Another barrier can be the smell, noise, and visual aesthetics complaints from community members after MSW facilities have been installed. The negative stigma has led to some difficulty in locating sites for these plants. Some national nongovernmental organizations (NGOs), such as the Sierra Club, believe facilities that use waste to convert to fuel lead to a disincentive for individuals and communities to recycle or reduce their consumption. Global Alliance for Incinerator Alternatives is a conglomeration of over 500 grassroots organizations opposed to incinerators as well as other waste technologies. They argue that the emissions associated with these facilities, including gasification, pyrolysis, and plasma arc fuel climate change, do not address the NGO's concern for overconsumption, and divert resources and focus from recycling programs. Most easily accessible information that drives public opinion is derived from these NGOs, which leads to a negative perception of these facilities. However, communities that have installed waste conversion facilities in their communities tend to have a more positive opinion of the technologies.

To reduce public resistance to these facilities, it would be helpful for companies to provide outreach to the public to educate them about technological advances and other positive aspects of these technologies. Some measures that may help include siting facilities at brownfields (i.e., abandoned or underused industrial and commercial facilities available for re-use), the use of dome designs to hide smokestack visibility, and integrated "utility campuses" that consist of sewage treatment, electricity generation, and water reclamation facilities (Lawrence, 2009). They may also need to control odors and noises emanating from operations through such measures as enclosed tipping floors and biofilter systems.

Some legislative actions are designed to encourage the development of conversion technologies. The federal government provides several grants and loans for feedstock development, biofuels, and biobased product development for technologies such as these conversion facilities. The Biomass Research and Development Initiative is one major source of funding. The initiative is an interagency effort of senior decision-makers from various federal agencies, including the U.S. Department of Agriculture (USDA) and U.S. Department of Energy (DOE) as well as the White House. The USDA awards loans to companies that demonstrate the potential benefits of their conversion technology processes. U.S. DOE provides funding for the conversion of biomass to various fuels, such as those produced through the use of conversion technologies. One company awarded a grant through this program is Enerkem. The company was also awarded an $80 million loan through the Biorefinery Assistance Program.

Another federal program designed to assist energy efficiency projects is the DOE's Federal Energy Management Program (FEMP). The objectives of FEMP are to lower government costs by advancing energy efficiency and water conservation and increasing renewable resource use. Agencies are guided by FEMP to use private sector financing for energy projects with the use of Utility Energy Service Contracts or DOE's Super Energy Savings Performance Contracts. Other federal assistance programs include EPA's Innovations Work Group, the National Center for Environmental Research, and DOE's Office of Energy Efficiency and Renewable Energy.

State and local governments also provide incentives for the development of alternative waste management approaches. For example, Iowa's Department of Natural Resources Land Quality and Assistance Division offers a loan program that "encourages implementation of innovative waste reduction and recycling techniques, develops markets for recyclable materials and products, and encourages the adoption of the best waste management practices" (U.S. EPA, 2011). Other states, such as California, provide extensive research and development opportunities for waste reduction. One such group is the California Energy Commission, which recently announced a $4.5 million grant to aid the development of an AD plant in Perris, California.

1.4 Report Structure

Sections 2—4 of this report present technologies by main category: pyrolysis, gasification, and AD, respectively. Each section contains a listing of known facilities in North America, profiles of selected facilities, data ranges that were defined after considering all the data obtained on these processes, and LCA results. It should be noted that we did not attempt to compare the performance of the various technology vendors based on the life cycle modeling results in **Sections 2—4.** Specific vendors were selected based on their relatively advanced stage of technology development and/or availability of information. Inclusion in this report does not signify endorsement by EPA. **Section 5** presents the overall findings and recommendations. **Attachment A** provides documentation for the scope, assumptions, and key data used to complete the LCAs for conversion technologies and landfill and conventional WTE base cases.

Section 2:
Pyrolysis Technology

Pyrolysis is defined as an endothermic process, also referred to as cracking, involving the use of heat to thermally decompose carbon-based material in the absence of oxygen. Its main products are a mixture of gaseous products, liquid products (typically oils of various kinds), and solids (char and any metals or minerals that might have been components of the feedstock). For its predominate use in North America on mixed plastics, liquid petroleum-type products predominate, which generally require additional refining. Application of pyrolysis to mixed MSW could potentially generate a gaseous mixture of carbon monoxide (CO) and hydrogen (H_2) called "syngas" that can be used for steam and electricity generation. Products of process are commonly reported, but the list and proportion of each differs depending on reactor design, reaction conditions, and feedstock.

Various technology vendors include different variations and names for pyrolysis processes in their technology descriptions, which can be confusing to waste managers. Technologies that are categorized as pyrolysis generally belong to one of the following process categories:

- ***Thermal pyrolysis/cracking***—The feedstock is heated at high temperatures (350–900 degree Celsius) in the absence of a catalyst. Typically, thermal cracking uses mixed plastics from industrial or municipal sources to yield low-octane liquid and gas products. These products require refining to be upgraded to useable fuel products.
- ***Catalytic pyrolysis/cracking***—The feedstock is processed using a catalyst. The presence of a catalyst reduces the required reaction temperature and time (compared to thermal pyrolysis). The catalysts used in this process can include acidic materials (e.g., silica-alumina), zeolites (e.g., HY, HZSM-5, mordenite), or alkaline compounds (e.g., zinc oxide). Research has shown that this method can be used to process a variety of plastic feedstocks, including low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), and polystyrene (PS). The resulting products can include liquid and gas products.
- ***Hydrocracking*** (sometimes referred to as "hydrogenation")—The feedstock is reacted with hydrogen and a catalyst. The process occurs under moderate temperatures and pressures (e.g., 150–400 °C and 30–100 bar hydrogen). Most research on this method has involved generating gasoline fuels from various waste feedstocks, including MSW plastics, plastics mixed with coal, plastics mixed with refinery oils, and scrap tires.

The process of pyrolysis creates residues including char, silica (sand), and ash. Some of these residues may be reused (if approved by an environmental agency) while others must be disposed of in a landfill. The amount of residual waste produced is about 15–20 percent of the overall [plastics] feedstock used in the process. Litter, odor, traffic, noise, and dust must also be assessed and will vary according to the differences in facility technology, size, and feedstock.

2.1 Existing Pyrolysis Technology Facilities and Vendors in North America

Existing pyrolysis facilities identified in North America are listed in **Table 2-1**. As shown in the table, the vendor name, status, accepted feedstock, location and main product output are listed. At the time of this study, there were three commercial-scale pyrolysis facilities in the U.S. including Agilyx, Intrinergy Coshocton, and JBI. Each of these facilities produces a petroleum (crude oil) type product that is, or may be, sold as a chemical commodity rather than used for producing energy.

2.1.1 Agilyx: Tigard, Oregon

Agilyx, formerly known as Plas2Fuel, was founded in 2004 and has an operating demonstration facility in Oregon. Agilyx claims to be able to use waste plastics of any type as feedstock and converts it into synthetic crude oil. According to the company, the plastic waste can be commingled and no pre-sorting or pre-cleaning is needed. The company estimates that approximately 10 tons of plastic may be converted to 60 barrels (or 2,400 gallons) of oil on a daily basis through a pyrolysis process.

Agilyx claims its system is able to handle any type of plastic feedstock and contamination level, thus reducing time and cost of the process. Agilyx uses custom-designed cartridges to convey feedstock to their processing equipment. Each system is modular and may be located at the collection facility to reduce costs associated with feedstock transportation. These systems may be scaled up or down, based on the amount of feedstock available.

Pre-processing of the plastic waste includes standard grinding and shredding to a density target of 20–21 lbs/ft^3. The cartridges are filled with plastic feedstock and inserted into a large processing vessel. A light industrial burner heats air to about 593.3 °C, and the air is circulated around the exterior of the cartridge while the plastics are transformed from a solid to a liquid, and finally a gas. In the gaseous form, the plastics have been broken down into oil-sized molecules.

The heating system is closed loop in order to diminish heat loss. The gases are drawn from the cartridge into a central condensing system. The gases are cooled in this system and condensed into synthetic crude oil. Char is extracted from the stream, while lightweight gases that do not condense continue downstream. The gases contain about 80 percent methane, propane, and butane species. The gases are then either combusted for heat recovery or treated by an environmental control device. The crude oil moves into a coalescing and settling process and is eventually moved to an above-ground storage tank outside the facility for transport to a refinery.

Agilyx's performance information includes a process energy ratio, which measures the British thermal units (BTUs) received from the process (output) for each BTU input to the process. According to the company's representatives, the process energy ratio (without including the energy value found in char) is about 5:1. With the energy value of the char included, the ratio is about 6:1. The BTU value of the crude oil produced is about 19,250 BTU/lb. The energy load requirements are purchased from the local utility company. Agilyx has the ability to generate both heat and electricity onsite (i.e., go off-grid), but their costs are lowered by purchasing

Table 2-1. Pyrolysis Facilities in North America.

Vendor Name	Status	Feedstock	Location	Main Product	Source (Sites accessed in June 2012)
Agilyx	Commercial	Plastics	Tigard, OR	Crude Oil	http://www.sustainablebusinessoregon.com/articles/2010/06/plas2fuel_opens_showcase_facility_changes_name_to_agilyx.html
Intrinergy Coshocton, LLC	Commercial	Blends of crumb rubber, shredded carpet fluff, wood chips, and biomass	Coshocton, OH	Crude Oil	http://www.rdno.ca/services/swr/docs/swmpr/waste_to_energy.pdf
JBI	Commercial	Plastics	Niagara Falls, NY	Diesel Fuel	http://www.plastic2oil.com/site/home
Envion	Demo (suspended)	PET, HDPE, LDPE/LLDPE, PP, PE, PS and PVC (less than 10%)	Derwood, MD	Crude Oil	http://inhabitat.com/new-envion-facility-turns-plastic-waste-into-10barrel-fuel/ http://www.envion.com/
Climax Global Energy	Demo	Plastics	Fairfax, SC	Crude Oil	http://blog.cleantech.com/sector-insights/waste/on-stage-in-new-york-climax-global-energy/
International Environmental Solutions	Demo	MSW	Romoland, California	Syngas	http://www.rdno.ca/services/swr/docs/swmpr/waste_to_energy.pdf http://www.bioenergyproducers.org/documents/ucr_emissions_report.pdf
Vadxx	Pilot Scale	Plastics, synthetic fibers, used industrial solvents, waste oils	Akron, OH	Crude Oil, natural gas	http://www.wksu.org/news/story/26888
Agriplas	Demo	Agricultural film, mixed nursery and jug material, food containers, and other low- or zero-value plastics	Kelso, WA	Crude Oil	http://www.green-energy-news.com/nwslnks/clips309/mar09019.html
Green Power Inc	Demo	Plastics	Pasco, WA	Crude Oil	http://www.cleanenergyprojects.com/Summary.html
International Environmental Solutions	Permitted	MSW	Riverside, CA	Syngas	http://dpw.lacounty.gov/prg/pressroom/printview.aspx?ID=370&newstype=PRESS
Oneida Tribe	Pilot Scale	MSW	Green Bay, WI	Syngas	http://www.greenbaypressgazette.com/article/20101102/GPG0101/11020584/Oneida-Seven-Generation-gasification-project-begins

power. Natural gas is used as a supplemental fuel during startup and emergency situations. Other fuels could be used as well.

According to data provided by Agilyx, (RTI, 2012), water requirements are minimal because it is recycled and filtered for contaminants. Sorbent cartridges, or wastewater treatment filters, are sent to a contractor to be cleaned and then are reused. No other inputs, such as catalysts, are necessary for the process. The primary residual in the process is char, and the company is attempting to find a commercial outlet for the product. About 8 percent of the feedstock generally becomes char, but the values can range from 1–50 percent, depending on the type of plastic used as feedstock.

Air emissions data reported by Agilyx (RTI, 2012) include permitted volatile organic compound (VOC), nitrogen oxide (NO_x), and carbon monoxide (CO) emissions. Particulate matter (PM) and sulfur dioxide (SO_2) are considered *de minimus* and are unregulated. Approximately 1,500 short tons per year of carbon dioxide (CO_2) are emitted from the light industrial burners. Agilyx is permitted to emit 39 short tons per year of nitrogen oxides and 39 short tons per year of VOCs but only discharge around 2.5 short tons of each pollutant. Agilyx is also allowed to emit 99 short tons per year of carbon monoxide, but actually emits about 1.5 short tons. Emissions of hydrogen chloride (HCl), SO_2, NO_x, and VOCs were stated by Agilyx to be based on a proposed limit, not actual emissions levels (see RTI, 2012).

At the time of this report, Agilyx is the only pyrolysis facility known to have a refinery off-take agreement within this industry. Currently, Agilyx is shipping crude oil from its facility in Portland, Oregon, to the U.S. Oil and Refining Co., located in the Pacific Northwest. The impacts of shipping and transportation costs in general were not researched in this study, but they suggest additional burdens that should be considered when evaluating the financial viability of the project.

2.1.2 Envion: Derwood, MD (to be relocated to Florida in 2011/2012)

Envion was founded in 2004 and focuses solely on the conversion of waste plastics to oil through a low temperature thermal pyrolysis process. The vendor cites advantages of the process to include relatively easy reactor construction and operation as well as the high efficiency and high BTU value of output products. One reactor began running in a demonstration capacity in 2009 at the Montgomery County Transfer Station (and appears to have ceased operations due to lack of continued funding). In terms of design capacity, an individual unit can process up to 10,000 tons of plastic waste annually. The company estimates that each ton of plastic may be converted to about 4 barrels of refined petroleum through a pyrolysis process. This technology can be scaled up or down through the addition of reactors. General process information for Environ was obtained from an RW Beck (2010) study.

The Envion technology uses chipped plastics as feedstock for the pyrolysis process. An illustration of the process is shown in **Figure 2-1**. The plastics must be chipped to less than 1.5 inches and melted. Approximately 1.22 tons of raw feedstock per hour is able to be processed. About 1.8 tons per hour are processed after water and contaminants are purged. The feedstock is composed of high-density polyethylene (HDPE), polypropylene (PP), low-density polyethylene (LDPE) plastics, and polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride

(PVC). PS, HDPE, LDPE, and PP are preferred because they provide the best oil yield. Only restricted amounts of PET containers are used because they lead to much higher values of waste product, mainly sludge. PVC plastics are also used in very small amounts due to the chlorine compounds released in the cracking process. Data are not available to determine the proportions of feedstock types but are thought to be comparable to typical MSW plastic composition in the U.S.

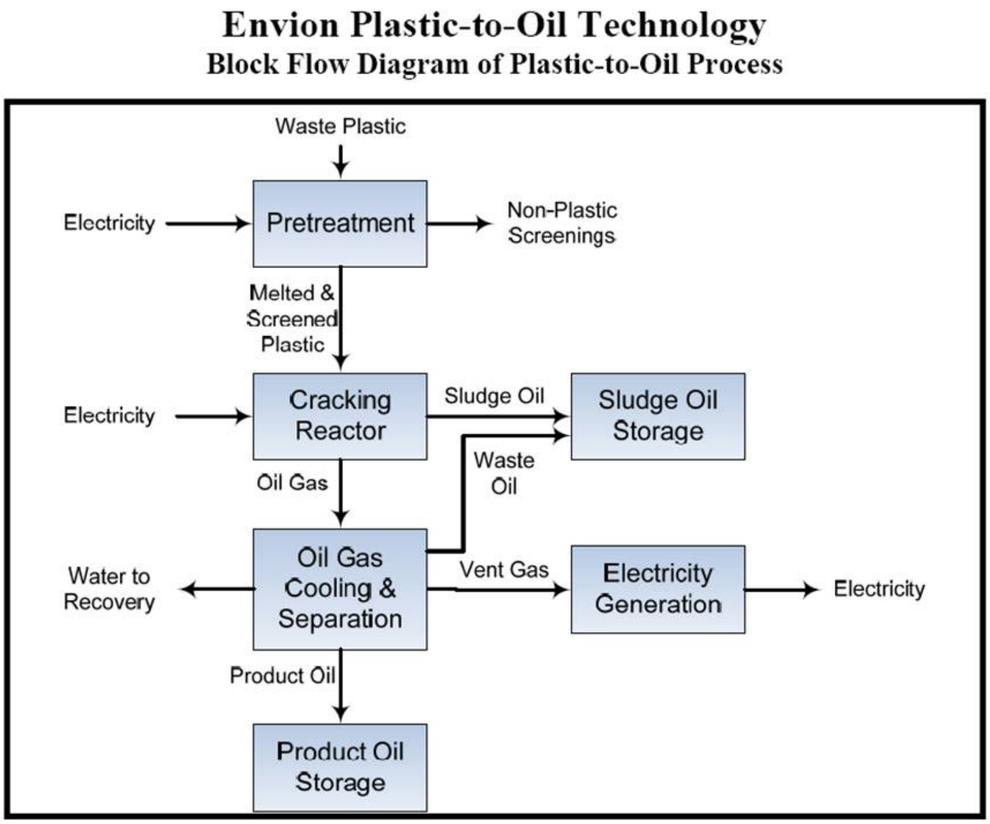

Figure 2-1. Envion Pyrolysis Process Flow Diagram.
(Source: www.envion.com)

In the pretreatment process, plastics move through a magnetic removal section and into the melting and screening section where they are liquefied at 300 °C. The plastics then go through a screen to filter nonplastic contaminants like glass and nonmagnetic metals. After the screening process, the plastic feedstock is fed into a reactor vessel where the plastics are subjected to low temperature thermal pyrolysis. Heat is introduced to the reactor vessel using far-infrared heaters. The resultant gas from the reactor vessel is then passed through a packed tower to remove contaminants. The gas is cooled and moved to tanks that separate reactor effluent into three streams: process gas stream, product oil stream, and water stream. Light components in the oil gas stream such as butane, propane, and methane exit the separation tank and are moved to an internal combustion engine (ICE) to produce electricity for the process. The efficiency of the ICE gen-set depends on the composition of the process gas. The product oil is eventually transferred to primary oil tanks. Waste oil and water contaminants condense to liquid form and are sent to the sludge tank.

The sludge oil tank remains at an elevated temperature so contents do not solidify. To empty the tank, some product oil is moved to the sludge oil tank to blend the oil so it may be moved to a heated asphalt transfer truck.

Other inputs for this process include about 750 KW of electricity and up to 0.435 tons of water per ton of raw plastic, depending on the amount of water needed for the cooling tower. Material byproducts include process gas that is currently used to offset 10–25 percent of electricity used in the process. The sludge byproduct accounts for about 15 percent of overall feedstock. Currently, the sludge is stored in barrels since the BTU value of the sludge indicates that it may have market potential as an energy source. Residuals include contaminants at a rate of 2 TPD, or about 8 percent of the overall feedstock.

Environ claims to convert 1 short ton of plastic into about 4 barrels of oil with a value of about 18,300 BTU (RTI, 2012),. The parasitic load is about 480 KWh/ton of waste after process gas has been combusted to generate electricity. The energy recovery efficiency of the Envion technology can be highly variable depending on the feedstock, but is generally about 62 percent.

Estimates of emissions as reported by the vendor are listed in RTI (2012) and include methane, sulfur dioxide, and nitrous oxide emissions. Mercury emissions are about 0.016 micrograms/ton of waste. Lead emissions are 0.106 mg/L of oil. Envion did not provide any information on water emissions. Sludge is currently considered a waste byproduct, although it has an energy value.

The cost per design capacity is estimated by the vendor to be $7.6 million per unit or $280,700/TPD. In terms of process cost per ton, estimates range from $17 to $60, assuming 80 percent of electricity use in the production process is from the grid. Costs would be lower if the process relied solely on their own power generation. If a market niche is found for the sludge byproduct it could possibly be sold, and this disposal costs would be reduced.

2.1.3 Climax Global Energy: South Carolina

Climax Global Energy is a company that exclusively uses plastics as their feedstock in order to produce high-quality synthetic oil and wax. Climax currently operates a demonstration facility and claims to be able to accept any type of plastic. Their source material comes from municipalities and private companies within a 50-mile radius. The company claims that no pre-cleaning or pre-sorting processes are necessary (although shredding is required); feedstocks are fed directly into a pyrolysis chamber. In order to power this process, microwave energy or diesel generators may be used. Vitrified solid residuals are one byproduct of this process. Approximately 5–10 percent of the original mass of the feedstock is nontoxic ash that must be landfilled.

Climax Global technology claims to be able to accept mixed, post-consumer plastics as feedstock for their pyrolysis process. The plastics must be chipped and shredded prior to being processed. Approximately 20 tons of raw feedstock per day is processed. Moisture content of the feedstock ranges from 0 to 5 percent. One ton of waste plastic yields 5 barrels of synthetic oil. The feedstock is converted using average bulk reactor temperatures of 400 °C. Inputs to the process include a minimal amount of inert nitrogen and 1–3 gallons of water per minute. Three to 4 tons of light gases (e.g., methane, propane) are produced as byproducts. One to 3 tons of solid carbonaceous residue and any inert materials from feedstock stream, such as rocks, dirt, and glass, are removed as a part of the process.

Climax Global Energy claims an energy recovery efficiency of approximately 75 percent. The commodity wax has approximately 6 million BTUs per barrel. The internal parasitic power requirement is expected to be about 18,000 KWh per day. No external fuel use is required in order for the facility to begin operations.

According to data reported by the RTI (2012), the facility emits PM, CO_2 and hydrocarbons, SO_2, N_2O, VOCs, NO_x, and CO. Byproducts of the process include inorganic residue and ash. Additionally, less than 1 gallon of water effluent per hour is produced during the process.

The cost per design capacity is estimated to be $250,000/TPD, including materials, handling, and other plant costs. Similar to the other pyrolysis operations profiled, Climax claims it is able to create many different products out of its plastic feedstock. For example, commodity wax is one product that has a variety of uses such as cosmetics, adhesives, and coatings. The company can also produce oils that can be refined into ultra-low sulfur diesel and high-grade synthetic lubricants such as automobile motor fuels.

2.1.4 JBI: Niagara Falls, New York

JBI uses a proprietary pyrolysis process, Plastic2Oil (P2O), to convert mixed, nonrecyclable plastic waste to fuel oil and naphtha. JBI receives feedstock from a variety of sources, including commercial and industrial partners, and is currently seeking a permit to use MSW-based feedstock. JBI has been operating at a commercial status in Niagara Falls, New York, since 2010 and anticipates one jointly-operated site in Canada and several in Florida. The P2O processor is highly automated and runs continuously, as long as feedstock is loaded into the hopper. Approximately 1,800 pounds of feedstock can be converted per hour. The process currently converts up to 20 tons of plastics per day. However, 30-ton-per-day units are in development. The footprint for the processing equipment is less than 1,000 square feet.

Feedstock is first shredded or pre-melted and conveyed to the reactor via a hopper and conveyor system. The reactor cracks the plastics into shorter hydrocarbons that are gaseous at the operating temperature of the reactor. After cracking, the heavy fraction gases are condensed and stored in fuel tanks and the light fraction gases are compressed and used to internally power the P2O process or are sold separately. Inputs include natural gas for start-up, proprietary catalysts, water and electricity. P2O is permitted to generate electricity onsite using process gases as fuel. Since the process can convert approximately 8 percent of the plastic feedstock into these light-fraction process gases, the grid electricity requirement averages around 67 KWh per ton of plastics processed.

According to data reported to RTI by JBI (RTI, 2012), for every ton of plastic processed, approximately 5 pounds of nonhazardous solids, 136 pounds of char (characterized by JBI as carbon black or pet coke), and spent catalysts are produced in addition to the naphtha, diesel, and light-fraction gases. Residues are removed automatically.

The Plastic2Oil process claims a recovery efficiency rate of approximately 92 percent (RTI, 2012). Each ton of plastic produces approximately 1,700 pounds of gasoline and diesel. Additional byproducts include residuals, which have been found to have a heating value of 10,600 BTU, and syngas. These products and byproducts may then be blended with other fuels and additives, depending on the market and/or needs of the purchaser. JBI also relies on the off-gases generated internally, reducing the operating costs and offsetting electricity grid mix emissions.

According to the RTI report (2012), primary air emissions from the P2O process include particulate matter, carbon dioxide, nitrogen oxides, hydrocarbons, and VOCs. However, JBI claims it is not required to monitor emissions or install emissions control technologies. In terms of GHG emissions, converting 1 ton of plastic using the P2O process is claimed by JBI to yield approximately 0.29 pounds of carbon equivalent emissions. The vendor also reports 2.41 pounds of NO_x emitted for every ton of waste plastics. JBI reports that the atmospheric emissions are less than those of a natural gas furnace. JBI claims water is used for gas cooling and wastewater from this step is reused, but no water effluent is generated.

The estimate for cost per design capacity is $587,000 for the entire machine. Operational costs to cold start and power the processing equipment average about $7 per hour. Plastics are generally provided to JBI at no cost.

In addition to receiving permits to begin commercial operations in New York, JBI recently announced a joint venture with OxyVinyl Canada to produce oil onsite using the waste plastics generated by OxyVinyl. JBI is currently focusing on creating additional partnerships with organizations that have existing permits and high-volume waste plastic streams to maximize consistent feedstock volume while minimizing the permitting processes.

2.2 Environmental Data and LCA Results

For the American Chemistry Council, RTI developed ranges for energy and emissions data for the pyrolysis technology category as a whole (see RTI, 2012). The data are shown in Table 2-2 and include ranges developed from a combination of vendor-supplied estimates, company web-pages, publicly available permit applications, and publicly available literature. Specific data provided by technology vendors is available in RTI's (2012) report.

The LCA methodology was used to guide the environmental and cost assessment. Using a life cycle perspective encourages planners and decision-makers to consider the environmental aspects of the entire waste management system. These include activities that occur outside of the traditional framework of activities, from the point-of-waste collection to final disposal. For example, anyone evaluating options for recycling should consider the net environmental benefits (or additional burdens), including any potential displacement of raw materials or energy. Similarly, when energy is recovered through waste combustion, conversion technologies, or landfill gas-to-energy, the production of fuels and the generation of electricity from the utility sector is displaced. For the pyrolysis technologies, commodity oils/waxes are the main product and thus we assumed that the commodity oils/waxes displace petroleum-based crude oil.

Table 2-2. Pyrolysis Process Data Ranges.

Parameters			Units	Value		
Process Inputs and Outputs						
Inputs	Power consumption/parasitic load		KWh/dry ton	0.3	-	480
Inputs	Other inputs (e.g., water, oxygen, etc.)	Water	gal/dry ton	30	-	216
Inputs	Supplemental fuel use	Natural Gas	MMBtu/dry ton			0.03
Outputs	Energy product (e.g., syngas, ethanol, hydrogen, electricity, steam)	Syngas	MMBtu/dry ton			0.2
		Crude oil	lb/dry ton	967	-	1362
		Light fraction (liquid)	lb/dry ton	300	-	400
		Gas fraction	lb/ dry ton	200	-	500
		Gasoline	lb/ dry ton			23
		Diesel	lb/dry ton			1,711
	Residuals (e.g., ash, char, slag, etc.)	Char	lb/dry ton	136	-	160
		Solid residues	lb/dry ton			160
		Inorganic sludge	lb/dry ton			300
		Nonhazardous solid waste	lb/dry ton			5
	Water losses		gal/dry ton			25
	Air Emissions Data					
	PM		lb/dry ton	0.04	-	15
	Fossil Carbon Dioxide (CO_2Fossil)		lb/dry ton	500	-	962
	Methane (CH_4)		lb/dry ton	26	-	65
	HCl		lb/dry ton			3.E-04
	Hydrocarbons		lb/dry ton	0.01	-	8
	Nitrous Oxide (N_2O)		lb/dry ton			2
	NOx expressed as NO_2		lb/dry ton	0.3	-	91
	Carbon Monoxide (CO)		lb/dry ton		-	9
	Lead		lb/dry ton	2.E-04	-	0.02
	VOC		lb/dry ton	3.E-04	-	2
Cost Data						
Cost per ton of design capacity			$/dtpd	29,350	-	280,699

LCA can be a valuable tool to ensure that a given technology creates actual environmental improvements rather than just transfers environmental burdens from one life cycle stage to another or from one environmental media to another. This analysis is also useful for screening systems to identify the key drivers behind their environmental performance.

The approach for constructing the LCA was to develop inventories of energy, emissions, and cost for the conversion technology system and to utilize the Municipal Solid Waste Decision Support Tool[4] (MSW DST), a tool developed under a cooperative agreement between RTI and EPA, to capture the other life cycle components (e.g., materials pre-processing [separation], landfill disposal, energy production, transportation, and materials production activities). The data and models in the MSW DST have been developed for the U.S. EPA and has gone through a series of reviews including external peer, quality assurance, administrative, and stakeholder reviews. Conversion technology results were then compared to results for base case landfill and conventional WTE scenarios. The landfill and WTE results are presented as a range. For

[4] https://mswdst.rti.org/index.htm

landfills, the lower end of the range represents disposal in a landfill with a gas collection and flaring system and the upper end of the range represents disposal in a landfill with a gas-to-energy type management system. For WTE, the lower end of the range represents facility with an efficiency of 18,000 btu/kwh and the upper end of the range represents facility with an efficiency of 14,000 btu/kwh. It is assumed that the electricity produced from WTE displaces electricity from utilities based on the U.S. average electricity grid mix of fuels.

The LCA results do not represent any one specific facility or vendor. Rather, data collected for selected technology vendors as profiled in **Section 2.1** were supplemented with data collected from the literature and lower–upper bound ranges were developed for the technology. Results include the transportation and disposal of residuals. Thus, the cost and LCA results include the burdens associated with the pyrolysis facility as well as with transportation and disposal of residuals. The benefits are those associated with fuels recovery.

The scope, assumptions, and key data are described in **Attachment A**. Results are presented in this section as net total burdens minus benefits. Therefore, negative energy results mean that more energy is recovered than that needed to run the processes; negative GHG emissions mean that there are more emissions savings as a result of energy and fuels production using the waste material relative to using virgin material; and negative cost results mean that the revenues are higher than the costs.

Energy

For pyrolysis, energy is consumed to power the process and ancillary systems and transport and dispose of residuals in a landfill. Energy in the form of petroleum products (e.g., fuel oil and petroleum wax) is the main output from the pyrolysis process. Typically this product is transported off-site for use.

The results for energy consumption for pyrolysis are shown in **Figure 2-2** on a per-ton basis and in **Figure 2-3** per MMBtu of energy produced. According to these figures, the petroleum product output generates large energy offsets. The pyrolysis process can be considered an energy producer (i.e., the energy produced exceeds the energy consumed), with some variation in the amount of energy produced, according to the data obtained from the vendors and the literature.

GHG Emissions

Consistent with the energy results, **Figures 2-4 and 2-5** show that pyrolysis of plastics results in GHG emissions savings, which are mostly due to emissions savings from the replacement of conventional energy (petroleum) products. The emissions data obtained for pyrolysis exhibits a wide range of variation, as illustrated by the minimum and the maximum bars.

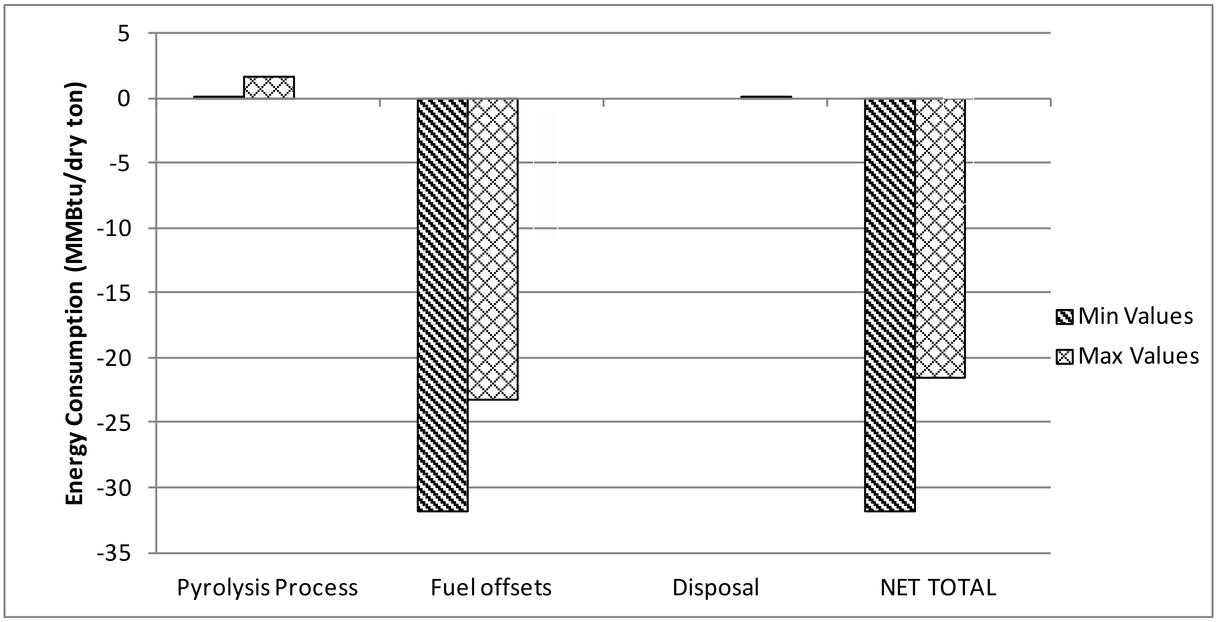

Figure 2-2. Net Energy Consumption Per Ton for Pyrolysis of Plastics.

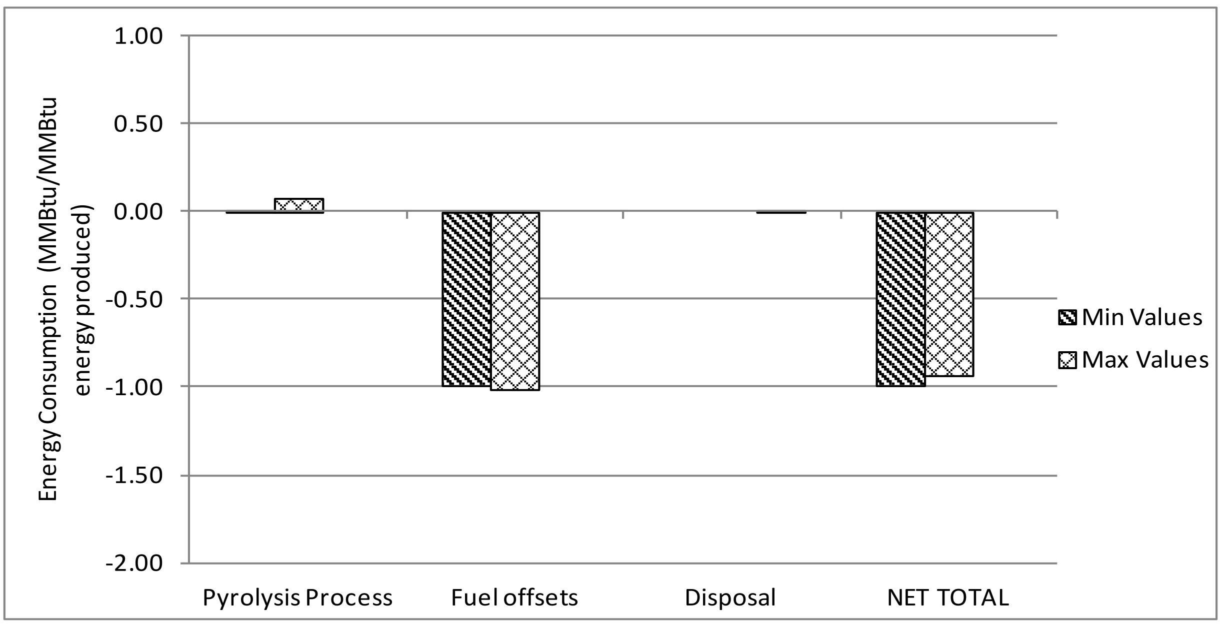

Figure 2-3. Net Energy Consumption Per MMBtu for Pyrolysis of Plastics.

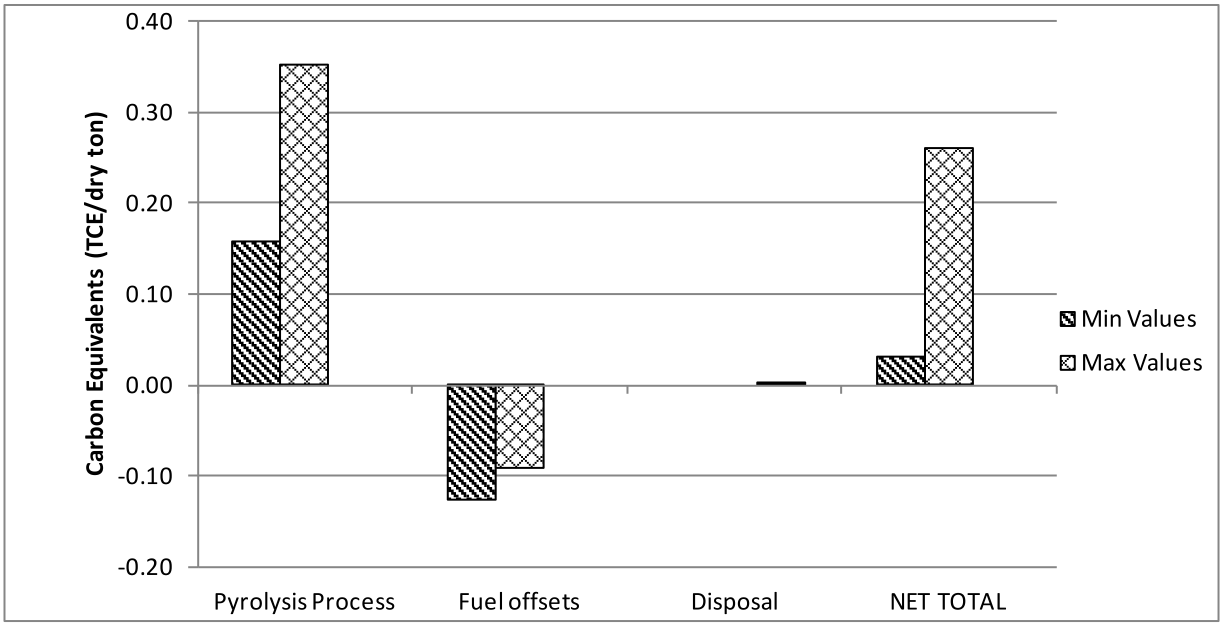

Figure 2-4. Net Carbon Equivalents Per Ton for Pyrolysis of Plastics.

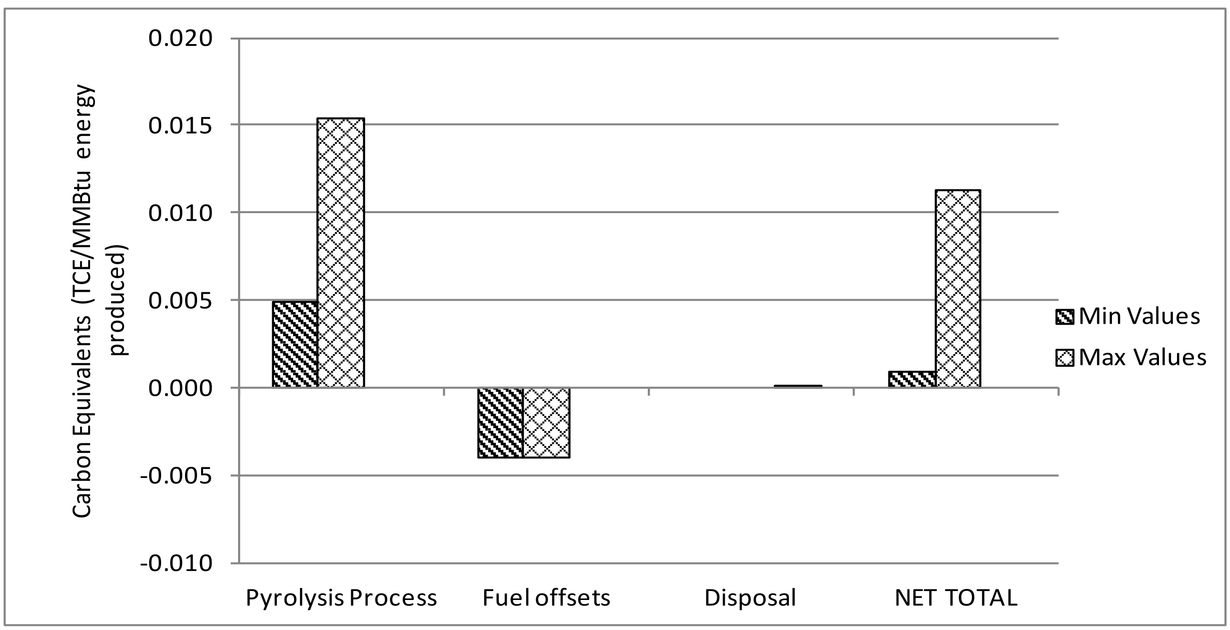

Figure 2-5. Net Carbon Equivalents Per MMBtu for Pyrolysis of Plastics.

Cost

The net cost (expenses minus revenues) per ton for pyrolysis of plastics is shown in **Figures 2-6 and 2-7**. As shown in these figures, the net cost range is negative, signifying a net revenue stream that results from the market value of the petroleum product being greater than the cost to process the plastics into petroleum via the pyrolysis process.

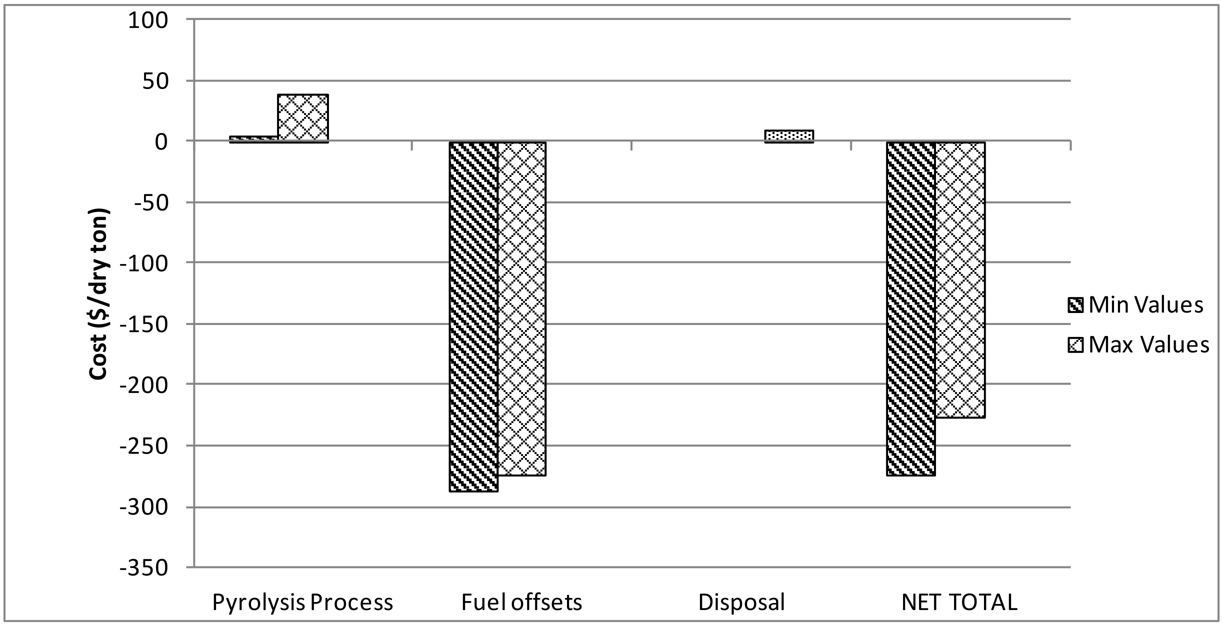

Figure 2-6. Net Cost Per Ton for Pyrolysis of Plastics.

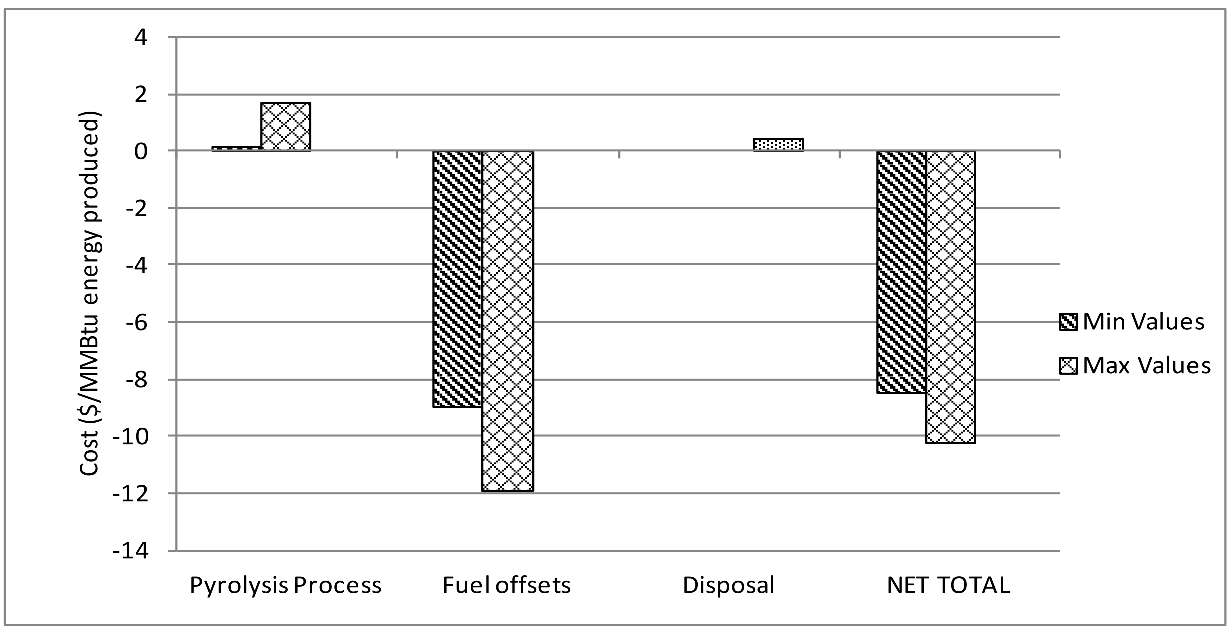

Figure 2-7. Net Cost Per MMBtu for Pyrolysis of Plastics.

The conversion efficiency (e.g., number of barrels of oil per ton of plastics) and contracted market price for the recovered petroleum product are highly significant to the net cost. Facilities will likely align their specific technology to obtain the specific petroleum product (e.g., diesel and petroleum wax) that yields the highest market price.

Comparison to Landfill and WTE Base Cases

In this section, the results for pyrolysis of plastics are compared to results for a landfill and WTE base case for plastics. A low–high range was developed for the landfill base case using a landfill with gas collection and flaring for the “low” end of the range and a landfill with gas collection and energy recovery for the “high” end of the range. However, since plastics waste isn’t expected to produce any gas, this distinction is not relevant and only done to be consistent with the gasification results. Again, the landfill base case was modeled using RTI’s MSW DST and is representative of a U.S. average. Similarly, a low-high range was developed for WTE using a plant efficiency of 14,000 btu/kwh as the “low” end of the range and a plant efficiency of 18,000 btu/kwh as the “high” end of the range.

Figure 2-8 shows the results for net energy consumption (i.e., energy consumed minus energy produced). According to this figure, the net energy saved using the pyrolysis technology versus landfill disposal is approximately 22–32 MMBtu per dry ton of plastics. These savings are mostly associated with the fuels produced by the pyrolysis facility and the fact that there is no energy recovery potential (i.e., there is no methane generation) from landfill disposal of plastics. When compared to WTE, pyrolysis appears to be in a similar range to WTE.

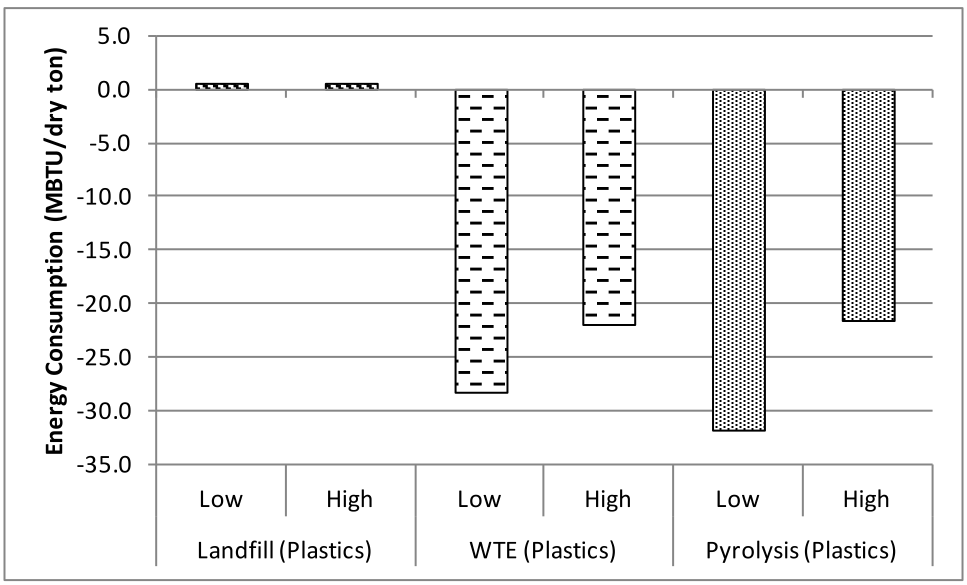

Figure 2-8. Net Energy Consumption for Landfill, WTE and Pyrolysis of Plastics.

Figure 2-9 shows the results for net carbon emissions (i.e., carbon emissions minus savings). According to this figure, the pyrolysis technology results in a net positive emission of carbon of approximately 0.03–0.26 TCE per dry ton of plastics processed when compared to landfills. This positive value is mostly associated with the crude oil produced by the pyrolysis facility and the fact that no carbon emissions are generated from landfill disposal of plastics. In the case of pyrolysis, the crude oil product may be combusted or used as a chemical feedstock to a manufacturing process. If used as a chemical feedstock, the carbon may be released to the

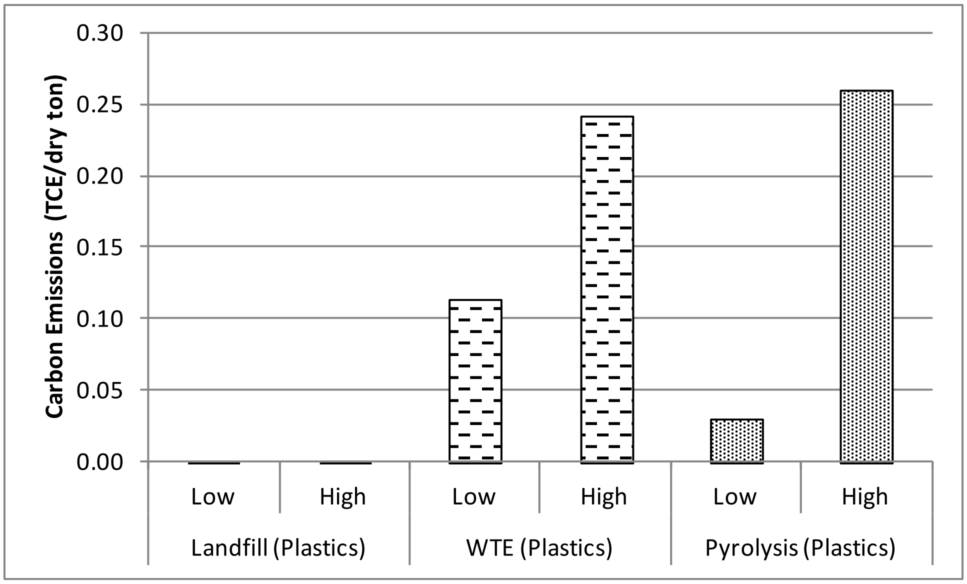

Figure 2-9. Net Carbon Equivalents for Landfill, WTE and Pyrolysis of Plastics.

atmosphere or possibly incorporated into the product. These results assume the carbon content of the crude oil ultimately is released to the atmosphere.

Figure 2-10 shows the results for net cost (i.e., costs minus revenues). According to this figure, the pyrolysis technology results in a net reduction of approximately $250–300 per dry ton of plastics processed when compared to landfills and WTE. Consistent with the energy and GHG emissions results, this reduction is mostly associated with the fuels produced by the pyrolysis facility. For example, the pyrolysis facility will obtain revenues from sale of the crude oil.

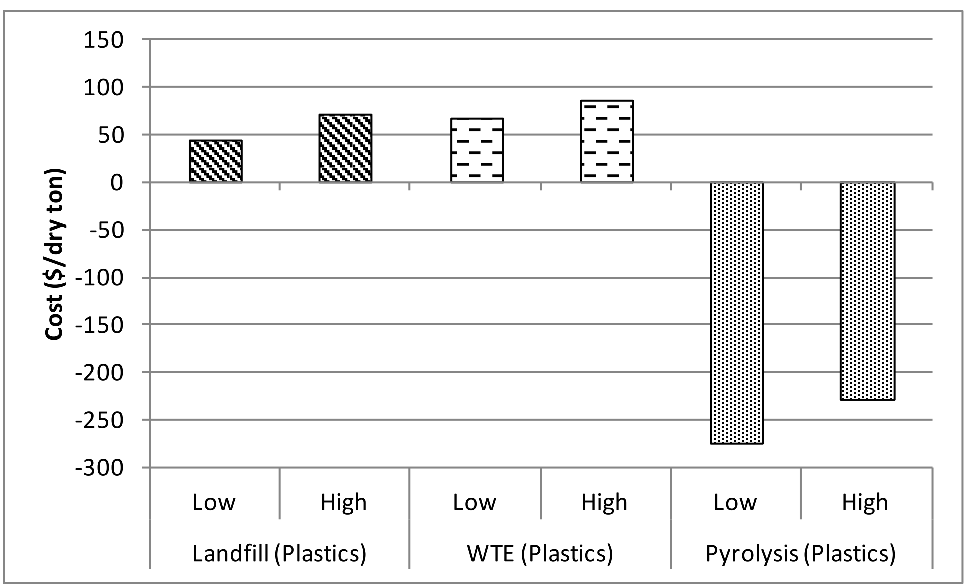

Figure 2-10. Net Cost for Landfill, WTE and Pyrolysis of Plastics.

Section 3:
Gasification Technology

Gasification is the partial oxidation of carbon-based feedstock to generate syngas. The process is similar to pyrolysis, except that oxygen (as air, concentrated oxygen, or steam) is added to maintain a reducing atmosphere, where the quantity of oxygen available is less than the stoichiometric ratio for complete combustion. Gasification forms primarily carbon monoxide and hydrogen, but potentially other constituents such as methane particularly when operating at lower gasification temperatures. Gasification is an endothermic process and requires a heat source, such as syngas combustion, char combustion, or steam. The primary product of gasification, syngas, can be converted into heat, power, fuels, fertilizers or chemical products, or used in fuel cells. The current main types of gasification processes for MSW include the following:

- ***High temperature gasification***—High temperature gasification reactors, as described in ARI (2007), can reach up to 1,200 °C and produce an inert byproduct, or slag, that does not need further processing to be stabilized. The syngas is typically combusted to generate steam which can be used for power and/or heat generation; however, the resultant sysngas may also be used for other applications such as chemicals production. Typically, this technology processes a mix of carbonaceous waste including paper, plastics, and other organics with a moisture content of up to 30 percent, which avoids the need for drying. In general, there are no water emissions because conventional water treatment systems are used to convert process discharges to useable process and/or cooling water. Treatment systems include settling and precipitation to capture and remove solids, which are returned to the high-temperature reactor.
- ***Low temperature gasification***—Low temperature gasification reactors, as described in ARI (2007) and RTI (2005), operate at temperatures between 600 and 875 °C and produce ash that could be sent to a vitrification process to make it inert and available for other uses. Syngas is the main product from this process and is typically used for electricity generation using an Internal Combustion Engine (ICE). This process can also recover steam energy. Separate estimates of energy from syngas and steam are obtained. This technology is assumed to require a feedstock with a moisture content of 5 percent or less and includes a drying pre-processing. A mix of gases and aerosols are produced from low temperature gasification and are sent to be quenched. The resulting liquid is cooled and water is recovered and sent to a solids mixing tank. Char, brine, and bio-oils may also be recovered. Bio-oils are typically recycled back to the process, but may be useful as fuel intermediates, and char and brine are included as water and solid waste emissions.
- ***Plasma gasification***—Plasma gasification converts selected waste streams including paper, plastics, and other organics, hazardous waste, and chemicals to syngas, steam, and slag. In this technology, the gasification reactor uses a plasma torch where a high-voltage current is passed between two electrodes to create a

high-intensity arc, which in turn rips electrons from the air and converts the gas into plasma or a field of intense and radiant energy with temperatures of thousands of degrees Celsius. The heated and ionized plasma gas is then used to treat the feedstock. Material such as petroleum coke is sometimes added to the reactor to support reduction reactions and to stabilize the slag. No drying pre-processing of the feedstock is required and the feedstock is assumed to have up to 30 percent moisture content. Syngas and steam are then typically used for power generation, included in the estimate of total electricity offsets. The slag, also produced in this process, is quenched prior to any use or disposal.

As with pyrolysis, residues such as slag and ash that are produced in the gasification process may need to be disposed of at a landfill. Another potential issue that may need to be assessed is the level of pre-sorting necessary. Some pre-processing will be needed for many of these facilities. For some gasification technologies, however, a significant presorting process will be required, including the removal of recyclables, sorting, shredding, and drying. The pre-sorting process is necessary to make the feedstock more homogenous and to increase efficiency of the overall process. The amount of material removed depends on the feedstock composition and the specific process requirements. Pre-processing, such as grinding, size classification, drying, or slurring, may be required to facilitate feeding of the feedstock into the particular conversion process being utilized.

3.1 Existing Gasification Technology Facilities and Vendors in North America

Existing gasification facilities identified in North America are listed in **Table 3-1**. As shown in the table, the vendor name, status, accepted feedstock, location and main product output are listed. At the time of this study, there were not any commercially operating gasification facilities accepting MSW in the U.S., however, there are a number of MSW-based facilities under development and testing. Each of these facilities produces syngas as the main product which is typically used for producing electrical energy. Liquid fuels, and other commodity chemicals are potential byproducts from gasification technology that may be marketable.

Table 3-1. Existing Gasification Facilities in North America.

Vendor Name	Status	Feedstock	Location	Main Product	Source (Sites accessed in June 2012)
Blue Fire Ethanol	Permitted	Wood chips, forest residuals, urban wood waste	Fulton, Mississippi	Ethanol	http://www.eere.energy.gov/golden/PDFs/ReadingRoom/NEPA/1%20Blue Fire%20DOE%20Final%20EA%206-4-10.pdf
Nexterra	Commercial	Wood residues	Heffley Creek, BC	Syngas	http://www.nexterra.ca/PDF/Project_Profile_Tolko_20100118.pdf
RangeFuels	Commercial	Non-food biomass, such as woody biomass and grasses	Soperton, GA	Syngas	http://www.rangefuels.com/range-fuels-produces-cellulosic-methanol-from-first-commercial-cellulosic-biofuels-plant.html
Cirque Energy LLC	Commissioned	Wood chips	Midland MI; Dow Corning	Syngas	http://www.dowcorning.com/content/news/midland_biomass_plant_dow_corning.aspx?bhcp=1
Alter NRG	Field Testing	MSW	Milwaukee, WI	Syngas	http://www.wisbusiness.com/index.iml?Article=209527
Taylor Biomass	Commissioned	paper, fiber, food residuals, leather, some textiles and wood products from MSW	Montgomery, NY	Syngas	http://www.taylorbiomassenergy.com/taylorbiomass04_mont_mn.html
Primenergy	Commissioned	Carpet Residues	Dalton, Georgia	Syngas	http://www.shawfloors.com/pv_obj_cache/pv_obj_id_D731E1B2C5B45ECE98332FBBC1FB427478F32A00/filename/EnviroBrochure2009.pdf
Westinghouse/ Coronal (subsidiary of AlterNRG)	Semi-commercial	MSW, WWT biosolids, and tires	International Falls, Minnesota	Syngas	http://alternrg.com/press_release_94443
Westinghouse/ Coskata subsidiary of AlterNRG)	Demo	Non-food based feedstocks, forest/ag waste and construction waste	Madison, Pennsylvania	Ethanol	http://www.westinghouse-plasma.com/technology/demonstration-facility
Enerkem	Demo	MSW, wood chips, treated wood, sludge, petcoke, spent plastics, wheat straw	Sherbrooke, Quebec, Canada	syngas, methanol, acetates, second generation ethanol	http://www.enerkem.com/en/our-locations/overview.html
Westing-house/Coskata	Demo	Building waste, forest waste	Warrenville, IL		http://www.coskata.com/facilities/?source=C3C8A85B-7736-4D64-87F8-9E4FBD45D1B0

Vendor Name	Status	Feedstock	Location	Main Product	Source (Sites accessed in June 2012)
InEnTech, LLC	Demo	MSW	Richland, WA	Syngas	http://www.inentec.com/pem-facilities.html
Plasco Energy	Demo	MSW	Ottawa, Canada		http://www.bioenergyproducers.org/documents/ucr_emissions_report.pdf
Ze-gen (operations have suspended as of September 2012)	Demo	MSW- wood wastes, non-recyclable plastics, carpet, and glycol (anti-freeze)	New Bedford, MA	Syngas	http://attleboroproject.com/qa.html
Enerkem	Demo	MSW/used electricity and telephone poles	Westbury, Quebec, Canada	Syngas	http://www.rdno.ca/services/swr/docs/swmpr/waste_to_energy.pdf http://www.bioenergyproducers.org/documents/ucr_emissions_report.pdf http://www.gemcanadawaste.com/52901.html?*session*id*key*=*session*id*val*
Fulcrum, InEnTech, LLC	Demo	Post-recycled MSW	Pleasanton, California	Ethanol	http://fulcrum-bioenergy.com/documents/IEReport-032610-FINAL.pdf
Ineos	Demo	Pre-processed MSW	Fayetteville, Arkansas	Ethanol	http://www.dep.state.fl.us/Air/emission/bioenergy/indian_river/INEOS_technical_evaluation.pdf
Nexterra	Demo	Sawmill residues	Vancouver, BC	Syngas	http://www.unbc.ca/releases/2010/11_25biomass_ignition.html
InEnTech /WM	Permitted	MSW	Columbia Ridge, OR	Syngas	http://www.inentec.com/images/stories/documents/PressReleases/releases--s4%20or%20announcement-march-2010_final.pdf
Entech Renewable Energy	Permitted	MSW	Huntington Beach, CA	Syngas	http://www.socalconversion.org/news.html
Ineos	Permitted	Yard, wood, agricultural and vegetative wastes	Vero Beach, FL	Ethanol	http://www.ineosbio.com/76-Press_releases-13.htm
Fulcrum, InEnTech, LLC	Permitted	MSW	Reno, Nevada	Ethanol	http://fulcrum-bioenergy.com/biofuel-plants.html
Enerkem	Permitted	MSW	Edmonton, Canada	Ethanol (as well as Syngas, Methanol, Acetates)	http://www.enerkem.com/en/our-locations/plants/edmonton-alberta.html
Enerkem	Permitted	MSW	Pontotoc, MS	Ethanol (as well as Syngas, Methanol, Acetates)	http://www.enerkem.com/en/our-locations/plants/pontotoc-mississippi.html

3.1.1 Enerkem: Westbrook, PQ, Canada

Enerkem's process is designed to convert waste materials to syngas as an intermediate product. Sources of feedstock include MSW, refuse-derived fuel (RDF) from sorted MSW, woody wastes from construction and demolition, used telephone poles, and other wastes from industrial, commercial, and institutional (ICI) processes. Electricity, ethanol, and other green chemicals are options for final products.

The company currently has two operational facilities including a pilot-scale demonstration plant in Sherbrooke, QC, Canada; and an operating commercial-scale demonstration plant in Westbury, QC, Canada. Enerkem also has begun construction on two additional facilities: one in Pontotoc, MS, and one in Edmonton, AB, Canada. According to Enerkem's website, the Pontotoc facility is currently finalizing permits required to build and operate the facility. The Edmonton facility is anticipated to begin full operations in 2013. Information regarding the status of the operations can be found on the City of Edmonton's and the company's websites. Another Enerkem facility is being proposed in Varennes, QC, Canada. All information about the anticipated Pontotoc, MS, plant was obtained from the Environmental Assessment (U.S. DOE, 2010). Information about the Canadian facilities was obtained from a combination of personal communications and literature search.

The commercial-scale demonstration facility has been in operation since 2009 and, in its demonstration stage, has managed approximately 39 tons per day of feedstock on a dry basis. [Source]Commercial-scale demonstration signifies that the facility is in the next-to-final stage of the technology development cycle and is a commercial-scale facility running smaller "batches" of waste to refine the process. The planned commercial facilities will have a capacity of approximately 330 dry tons per day.

The Enerkem gasification process is illustrated in **Figure 3-1**. The first steps in the process are to dry, sort, and shred the waste. Three types of feedstock are used: (a) refuse-derived fuel (RDF) that has been sorted from MSW, (b) construction and demolition (C&D) waste, and (c) institutional, commercial, and small industry (ICI) waste. The pre-sorting of RDF waste includes sorting and biological treatment followed by processing to a "fluff." The facility can also accept more traditional pelletized RDF. C&D wood is shredded and ICI is sorted and also shredded. All pre-processing occurs at the facility. The inorganic matter content of each type of feedstock is generally 15 percent of total weight for RDF and ICI, while C&D wood is less than 5 percent.

The shredded "fluff" from MSW, C&D, and ICI waste is fed into a bubbling fluidized gasifier. The waste is converted into syngas. Inert residues are removed and can be used as aggregate for construction (if approved). Next, the syngas goes through a series of steps that clean and condition the syngas. These systems include cyclones, a cooling system, water treatment, and a washing tower. Wastewater is a main byproduct of this portion of the process, but is reused. Enerkem claims the heating value of syngas is between 6 and 12 megajoules per standard cubic meter, depending on the process specifics. Electricity can be produced with the use of syngas in an internal combustion engine (ICE) generator-set. Alternatively, the syngas can enter catalytic reactors where it is converted into liquid fuel including ethanol, advanced biofuels, and/or green chemicals. Conversion to ethanol requires oxygen and steam inputs for this step of the

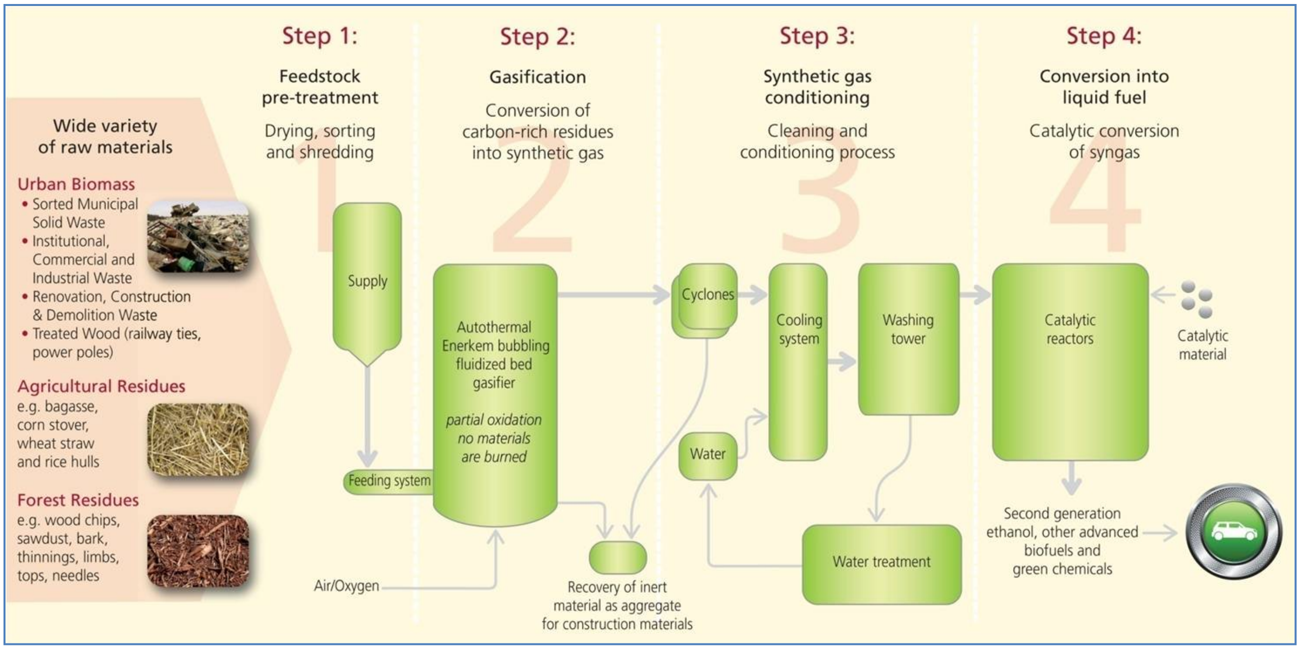

Figure 3-1. Enerkem Gasification Process Flow Diagram.
(Source: http://enerkem.com/en/our-solution/technology/process.html)

process. The exact process configuration and end product(s) will be tailored to the markets and contractual arrangements.

Performance information provided by the vendor includes the efficiency of the process in terms of efficiency of conversion into final products on a calorific basis, as well as the reliability of the technology in commercial operating conditions. Enerkem states that 72% of the lower heating value (LHV) of the feedstock is converted to syngas. In addition, high- or low-grade heat recovery is an option that Enerkem states can provide 5–10 percent of additional conversion efficiency. The internal parasitic power requirement to operate the gasification process is approximately 600 KWh per dry ton when electricity is the end product and 490 KWh per dry ton when ethanol is the end product. In addition, natural gas is required (15.72 lbs per ton of MSW) for facility start-up, but is not used as a co-fuel for normal process operation.

Since Enerkem is operating as a demonstration facility, information about the reliability of the process at commercial operating conditions is not available at this time.
In general, the data quality for emissions estimates is low since the facility is still in the demonstration stage. As the facility transitions to a fully operational commercial stage, one would expect the process inputs/outputs to stabilize and emissions to be more consistent for measurement.

Primary air emissions from the Enerkem process include CO_2 and NO_x as well as traces of methane, HCl, hydrocarbons, SO_2, and CO. The vendor indicated to RTI that mercury, cadmium, lead, ammonia, dioxin, and furan emissions are all below Canadian and U.S. (and EU) regulatory limits. Ammonia is also an emission that must be controlled using a scrubber system. The ammonia then must be removed from the circulating scrubbing water. The recovered ammonia (NH_3) can be sold or reintroduced in the gasifier, where it is converted into nitrogen (N_2) and hydrogen (H_2). A steady state level of NH_3 is thus achieved and the syngas maintains a concentration below the regulations.

In terms of GHG emissions, Enerkem estimates (American Chemistry Council, 2012) that approximately 40 percent of the carbon in the feed is turned into CO_2, but approximately 75 percent of the produced CO_2 is recovered and reused. The ratio of biogenic to fossil carbon in CO_2 depends on the ratio of biogenic to fossil material in the RDF feed stream. Enerkem also indicated (see RTI, 2012) that the biogenic to fossil carbon fraction is typically 3- 4 to 1 for the RDF since it contains about 20 percent plastics and 60 to 70 percent biomass.

Water is used for gas cooling and wastewater from this step is reused. The process itself is a net water producer. Enerkem estimates that it purges 1 ton of process water per ton of feed (dry basis). The facility cleans this water and returns about 80 percent of the purged water to the process. The remaining excess water generated is evaporated in a cooling tower or discharged as wastewater. Enerkem data provide a range of 544 to 1,270 pounds of water generated per ton of waste processed, depending on the moisture content removed in the drying/dehydrating step.

Residual wastes produced by the process include primarily char and spent or residual catalysts from the catalytic synthesis stage. No estimate for char production was provided, but the char would require disposal. If the process is tailored to produce alcohol fuels as the main product, then residual catalysts would be produced and also require disposal.

Estimates for capital and operating costs were collected through publicly available sources as well as from the American Chemistry Council (2012). Similar to emissions, reliable cost estimates are difficult to present since the facility is still in the demonstration stage. As the facility transitions to a fully operational commercial facility, one would expect the process inputs/outputs to stabilize and costs to be more consistent and reliable.

Estimates for cost per design capacity for the Enerkem Pontotoc, MS, facility is $424,000 per dry ton. For their 330 dry ton per day facility, the total capital cost would be approximately $140 million. Additionally, an external source presentation indicates Enerkem receives feedstock at no cost or at a gain of approximately $45 per ton of waste for the Quebec facility.

Electricity, ethanol, and other green chemicals are options for final products for the planned facilities. The exact process configuration and operation specifics will be tailored to the markets and contractual arrangements.

3.1.2 Plasco: Ottawa, Ontario, Canada

Plasco Energy Group operates a commercial-scale demonstration facility working closely with the city of Ottawa. The partnership began in April 2006 and the facility was constructed at the site of the operating Trail Road Landfill. Currently, the facility is permitted to process 93 ton per day of solid waste and is designed to generate 4 MW of electricity. Plasco Energy Group provided RTI with an independent comparative analysis of Plasco and other waste-to-energy (WTE) facilities as well as with a process brochure (Pembina, 2009; Plasco, 2011). Additionally, general process information and semi-annual emissions reports were obtained from the company’s website (Plasco, 2010).

Plasco Energy Group's Ottawa Trail Road Facility is a WTE facility that utilizes non-recycled MSW. MSW is first shredded and then goes into the conversion chamber, which converts waste into crude syngas with the use of recycled heat. A plasma torch is used to heat and stabilize residual solids liberates any remaining volatile compounds and fixed carbon into crude syngas, which then flows back to the conversion chamber.

The crude syngas moves to the refinement chamber and plasma torches are utilized to clean and refine the gas. At this point, the syngas is passed through several unit operations designed to remove heavy metals, particulate matter (PM), and acid gases. After cleaning, the Syngas is routed to either a flare, or an ICE to generate electricity. A percentage of the process water must be disposed of through a licensed carrier, or permitted for treatment at a POTW. However, Plasco will be a net producer of water because the excess moisture in the waste is removed at high temperatures. The water is then filtered and cleaned to sewer water standards.

The process flow diagram for Plasco is **Figure 3-2**.

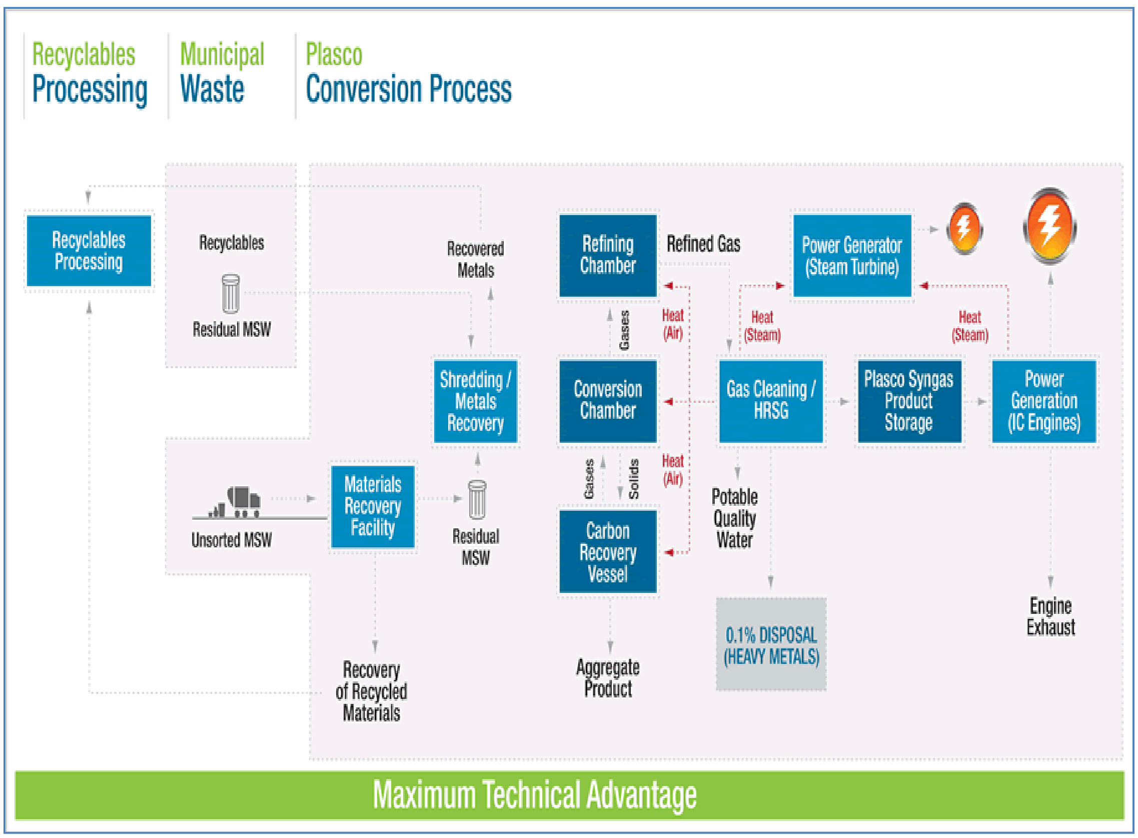

Figure 3-2. Plasco Gasification Process Flow Diagram.

(Source: www.plascoenergygroup.com)

No data were obtained for the energy conversion efficiency of the process. However, Plasco reports that 98 percent of the waste processed is converted to marketable products. Additionally, a 2009 study comparing Plasco to standard waste-to-energy processes indicates that each ton of waste produces between 2,000 and 3,000 cubic meters of syngas with an energy content of 3 to 5 megajoules per cubic meter, depending on the feedstock content. Higher energy content in feedstock yields higher energy content and higher volumes of syngas. If accurate, syngas would yield approximately 3,200 to 7,900 BTUs per pound of waste. This estimate is significantly less than what other gasification vendors are claiming. However, the study estimates that when used to generate electricity, the Plasco process produces more energy per ton of input, than mass burn WTE or landfill gas to energy.

Slag is one residual from the Plasco process. Plasco claim the slag is transformed to pellets, which are inert vitrified, or glass, residues. Converter ash is a byproduct that is also produced when the carbon recovery vessel (CRV) is not running. The ash is then landfilled. Baghouse ash is sent offsite as hazardous waste.

No cost information for the Plasco technology was provided; however, the website indicates that approximately $270 million in capital has been raised and invested in Plasco since 2005. Additionally, an external source presentation[5] indicates that capital costs are approximately US$86/ton of waste.

Since the Plasco facility is still in a demonstration phase, details of the facility's operations may not necessarily be representative of the actual levels of efficiency and waste outputs that will occur under a commercial facility. Although the demonstration facility may not perform as well as the planned commercial-scale one, a technical review conducted in 2009 displayed results in favor of Plasco's operations (see Pembina, 2009). An independent research organization conducted an analysis of the commercial version of the current demonstration facility in comparison with incineration, AD, and landfill gas with gas capture facilities located around the world (Pembina, 2009). The life cycle analysis results showed that air emissions were lower or about the same for Plasco when compared to other systems, with the exception of heavy metals and PM. Plasco had a heightened ability to generate a greater energy value per waste unit. The company was also capable of generating more marketable products from a given waste stream, and was also able to remove more sulfur, heavy metals, and PM before combustion than the other companies. The results of the study lead to a favorable conclusion of Plasco's planned commercial-scale facility in terms of environmental effects and efficiency levels.

3.1.4 Ze-gen: Attleboro, MA (Operations Suspended As Of September 2012)

Ze-gen was founded in 2004. The company was expected to complete construction and begin operations in 2012 of the Attleboro Clean Energy Project, located within the Attleboro Corporate Campus in Massachusetts.. However, declines in natural gas prices and difficulties obtaining permits led to the cancellation of the project. The city council banned any gasification plant on account of potential "toxic dust." The facility was going to be co-located with an industrial wastewater treatment facility. The design capacity was expected to be between 75 and 150 tons per day. The energy products were expected to be steam and synthesis gas (syngas) with one-quarter the energy density of natural gas and expected to replace natural gas. The company also has a demonstration facility, mainly for research and development, located in New Bedford, MA, that opened in 2007.

[5] http://www.seas.columbia.edu/earth/wtert/meet2010/Proceedings/presentations/CASTALDI.pdf.

Ze-gen will construct a liquid metal gasification facility that utilizes post-recycled, processed waste material. The facility will accept the following feedstocks: creosote treated railroad ties, nonrecyclable plastics, and clean wood waste. Pre-processing of the feedstock will be necessary and will occur through a contracted processer off-site. After pre-processing is complete, the moisture content of the feedstock will be less than 20 percent and the inorganic matter content will be less than 5 percent. Other inputs are required in order to achieve air emissions control, such as sodium hydroxide, calcium hydroxide, aqueous ammonia, and activated carbon.

Synthesis gas (syngas) will be created through a thermo-chemical process with the use of liquid copper. The temperature of the gasifier will be about 1,204 °C. The process of gasification will divide organic and inorganic components. The organic components will be reformulated to produce syngas, while inorganic components will be removed. The syngas will be used in a boiler that will produce steam and power a generator to yield electricity.

The Attleboro Clean Energy Project is expected to have an energy recovery efficiency of approximately 48 percent. The internal parasitic power requirement is expected to be less than one MW. The regional electricity grid mix displaced by delivered electricity is 9 percent coal, 38 percent natural gas, 25 percent oil, and 14 percent hydroelectric power and renewable. In order for the facility to begin operations, supplemental fuel use will be necessary at a rate of approximately 1,500 MMBtu of natural gas per startup.

Ze-Gen's process emissions will be regulated by the Massachusetts Department of Environmental Protection and will include PM, CO_2, CH_4, HCl, NO_x, VOCs, CO, NH_3, mercury (Hg), cadmium (Cd), and lead (Pb). Massachusetts does not treat biogenic carbon emissions as neutral, unlike most other states. In their report, Ze-gen computes carbon contributions in three ways: avoided emissions, total carbon + biogenic, and carbon without including biogenic emissions. Ze-gen provided a range of emissions, and for this report the upper bounds of emissions levels were used. Wastewater will be another byproduct of the gasification process, and will occur at a rate of about 45 gallons per minute. Residuals will also be present from those inorganic components that have been removed from liquid metal. The components will be made into vitreous glass-like slag. About 1.5 tons of slag is expected to be generated per day.

No cost information for the Ze-gen technology was provided or found through literature and Web searches. Currently, Ze-gen is testing the viability of using various feedstocks, including its ability to use marine debris plastic floating along the surface of the ocean. If successful, the company could remove some of the waste that is detrimental to the overall ecosystem health of the ocean while converting waste to usable fuel.

3.1.5 Geoplasma: St. Lucie, Florida [No longer in development at time of this report]

Jacoby Development, Inc. formed Geoplasma, LLC in 2003 in order to work on research and development for conversion technologies. Geoplasma is a planned facility that has received its final air permit from the Florida Department of Environmental Protection. The facility is set to produce 22 MW of power with the use of 600 tons of waste on a daily basis. Geoplasma, St. Lucie will be constructed at the St. Lucie County Solid Waste Facility. All information about the anticipated St. Lucie plant was obtained from the Environmental Assessment (U.S. DOE, 2010).

The facility will use Class I waste, which in Florida includes solid waste that is not hazardous and waste not banned from disposal in a lined landfill. It will also process construction and demolition (C&D) waste, tires, and yard waste. Geoplasma will reduce monetary and time costs associated with transport of waste to the facility because they will be co-located with the waste facility. The feedstocks will be received in the existing receiving and baling recycling building. Supplementary storage will be constructed similar to the existing one. A conveyer system will transport waste fuel to the initial processing location to reduce the size of the material. The moisture content of the feedstock value is assumed to be 30 percent. In order to minimize fugitive emissions and odors, air for the gasifier will be pulled from the waste processing area and conveyer system.

The waste will also be mixed with coke and limestone. Coke will be necessary to mix with MSW and tire fuel to have a porous bed at the bottom of the gasifier. Limestone will be used in the flue gas desulfurization (FGD). The mixed feedstock will be fed into the plasma heat gasifier. The organic constituents will undergo a conversion process into a syngas, which will then be combusted in a multi-stage thermal oxidizer, and then a heat recovery steam generator (HRSG) to produce high-pressure and high-temperature steam. The steam will power a steam turbine electrical generator that will supply electricity to the grid. Exhaust gas from the HRSG will be filtered through an emissions control system before it is discharged to reduce harmful pollutants.

No information on the energy performance of Geoplasma's anticipated facility was supplied by the vendor; however, the Florida Department of Environmental Protection (FL DEP, 2011) cites that the facility is anticipated to produce approximately 22 MW of power from approximately 600 tons per day of waste.

According to a Florida Department of Environmental Protection construction permit application (FL DEP, 2011), Geoplasma is considered a source of hazardous air pollutant (HAP) emissions and is in accordance with Title V a major source category. No water emissions data were available. Since the facility is not yet functioning, the potential to emit value was used instead of actual emissions levels. The facility was also assumed to be operating 312 days a year on a 24-hour basis. Emissions that have limits include NO_x, CO, SO_2, VOC, HCl, PM, Lead, Hg, Cd, dioxins and furans (D/F), visible emissions (VE), and NH_3. Limestone is used in air pollution control equipment to minimize SO_2 emissions. Another input is powered activated carbon (PAC) delivery, which will be used to manage Hg, trace metals, and complex organic compounds.

Byproducts of the plasma gasification process include vitrified inorganic residue. The bottom of the gasifier will also discharge some residue metals into water. Sand-like aggregate and metal nodules will be produced from this mixture at a rate of 13,200 lb/hr. The two byproducts are planned to be separated, stored, and loaded into trucks to be sold offsite. Spent PAC will be accumulated in the system baghouse and moved to a storage silo at a rate of 900 lb/hour. In order to reduce PM emissions, the PAC will be transferred through an enclosed conveyer to the silo. Gypsum is another process byproduct, and is expected to be produced by the FGD system at a rate of 900 lb/hour.

The Geoplasma data collected was not analyzed during this analysis for several reasons. Most importantly, the Geoplasma process data were the only data we were able to collect for the plasma arc process. Additionally, we were not able to obtain all of the process information needed for the LCA.

No cost information was provided by the company and was not available at the time of this report. According to the public's comments on the draft permit, support for the facility is widespread. One potential issue that may need to be addressed in the future is that excess emissions are allowed during startup, shutdown, or malfunction. The Blue Ridge Environmental Defense League specifically cited that this flexibility in emissions levels is unacceptable. If there are issues during Geoplasma's operations that lead to significantly higher emissions, it is possible that this issue may come up again.

3.2 Environmental Data and LCA Results

For the American Chemistry Council, RTI developed ranges for energy and emissions data for MSW gasification technology category as a whole (see RTI, 2012). The data are shown in Table 3-2 and include ranges developed from a combination of vendor-supplied estimates, company web-pages, publicly available permit applications, and the open literature. Specific data provided by technology vendors is available in RTI report.

LCA results for energy consumption and GHG emissions (as carbon equivalents), as well as cost are presented and discussed in this section of the report. The key data and assumptions for the LCA and those specific to gasification are included in **Attachment A**. Results are presented as net total burdens minus benefits. LCA results are also presented on a per dry ton basis as well as per unit of energy produced (1 MMBTU) basis.

The cost and LCA results for energy and GHG emissions for gasification of MSW are presented in this section. Since gasification technologies typically accept MSW that must be pre-processed, recyclables are recovered and residual unwanted wastes must be disposed. Thus the cost and LCA results include burdens associated with the pre-processing of MSW, as well as the transportation and disposal of residuals. The primary driver of the difference in gasification emissions per ton of MSW is driven by feedstock differences and has less to do with the process, unless plastics are removed. The benefits include not only the electricity recovered. Since we assumed the facilities would accept post-recycling MSW, potential recovery of additional recycles was assumed to be minimal and therefore not included. However, if a facility accepted MSW that contained a significant amount of recyclable material, it could potentially be recovered for recycling and create additional benefits.

Table 3-2. Gasification Process Data Per Dry Ton.

Parameters			Units	Value		
Process Inputs and Outputs						
Inputs	Power consumption/parasitic load		KWh	200	-	490
	Other inputs (e.g., water, oxygen, etc.)	Oxygen	lb			1,446
		Catalysts and chemicals	lb			107
		Diesel for preprocessing	gal			0.05
		Caustic for gas cleaning and cooling	lb			10
		Activated Carbon for gas cleaning and cooling	gal			0.2
		Feldspar for gas cleaning and cooling	gal			0.1
		Water	gal	540	-	1,622
	Supplemental fuel use	Natural Gas	lb	16	-	87
Outputs	Energy product (e.g., syngas, ethanol, hydrogen, electricity, steam)	Electricity	KWh	925	-	1,302
	Material byproducts	Residual gas	lb			428
		Sulfur	lb	2.6	-	2.7
		Salt	lb	9	-	13
		Slag	lb	24	-	424
	Residuals (e.g., ash, char, slag, etc.)	Char	lb			297
		Slag	lb			75
		Gasifier solid residues	lb	25	-	120
		Spent catalysts and chemicals	lb			3
		Inorganic sludge	lb			45
		Nonhazardous solid waste	lb			13
	Air Emissions Data					
	PM		lb	0.01	-	0.35
	PM10		lb			0.001
	Biogenic Carbon Dioxide (CO2bio)		lb	lb		
	Fossil Carbon Dioxide (CO2fossil)		lb	lb	-	1,048
	Methane (CH4)		lb	2.E-04	-	2
	HCl		lb	0	-	0.03
	Sulfur Dioxide (SO2)		lb	0	-	0.4
	Sulfur Oxide		lb			5.E-05
	Nitrous Oxide (N2O)		lb	0.001	-	0.40
	NOx expressed as NO2		lb	0.2	-	1
	Carbon Monoxide (CO)		lb	0.1	-	1
	Mercury (Hg)		lb			6.E-07
	Cadmium (Cd)		lb			8.E-06
	Lead		lb			1.E-05
	VOC		lb	1	-	0.04
	HAP		lb			0.1
	Acetaldehyde		lb			0.1
	Total non-methane organic carbon (TNMOC)		lb	0	-	0.2
	Dioxins and Furans		lb			0
	Water Emissions Data					
	Water Effluent		gal	600	-	1,400
Cost Data						
Cost per design capacity			$/dtpd	499,109		

Energy

For gasification, energy is consumed to pre-process the incoming MSW, power the gasifier and ancillary systems, transport residuals, and dispose of residuals in a landfill. Energy in the form of syngas is the main output from the gasification process. Typically this syngas is combusted onsite in an internal combustion engine (ICE) generator set (gen-set) to produce electricity. This is the process modeled in the LCA. The syngas can be directly used or converted to liquid fuel, but these options were not modeled because they are less common.

The net energy consumption results for gasification are shown in **Figure 3-3** on a per-ton basis and in **Figure 3-4** per MMBtu of energy produced. As shown in the figures, the energy (in the form of electrical energy) produced from the gasification process generate significant energy offsets. The gasification process itself is a net electricity producer (i.e., the energy produced exceeds the energy consumed) with some variation (according to the data obtained from the different vendors and the literature) in the amount of energy produced in the range of 6-12MMBtu per ton of MSW input or approximately .6-.9 MMBtu per MMBtu of energy produced.

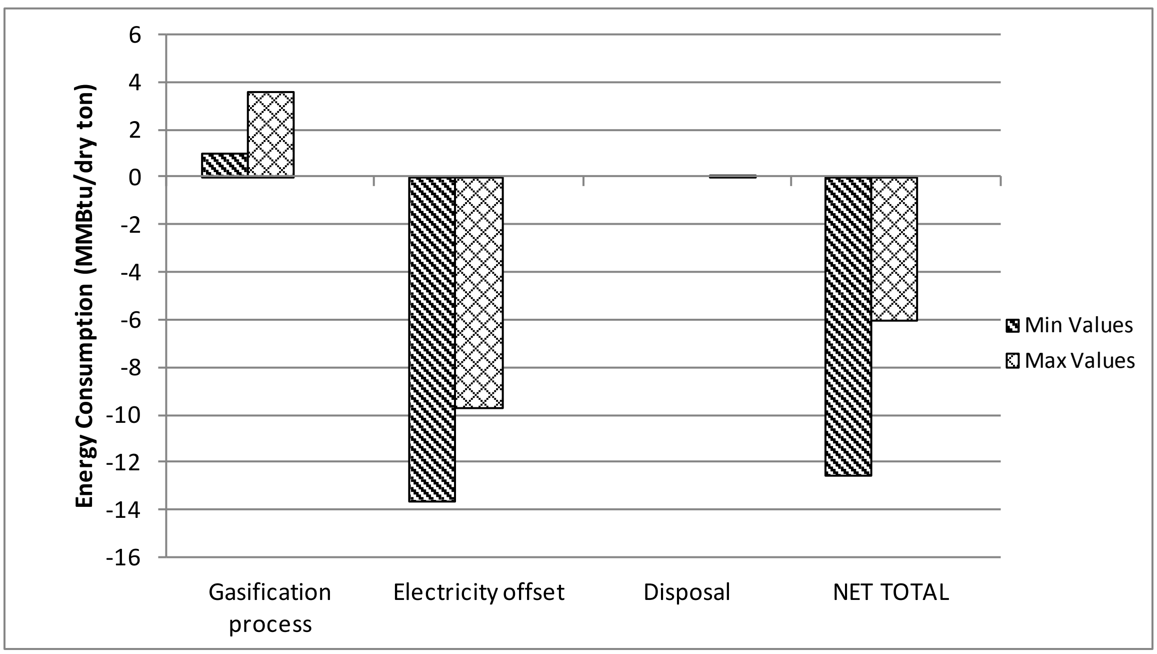

Figure 3-3. Net Energy Consumption Per Ton for Gasification of MSW.

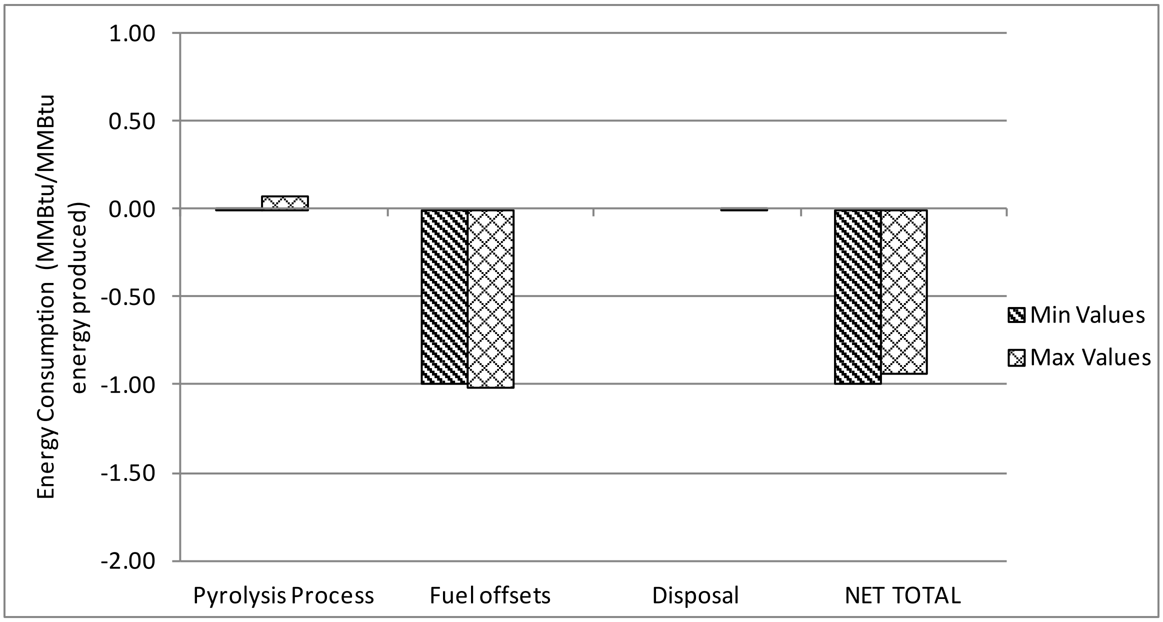

Figure 3-4. Net Energy Consumption Per MMBtu for Gasification of MSW.

GHG Emissions

Figures 3-5 and 3-6 show the gasification process producing a net GHG emissions savings at the lower end of emissions generation from the process, which results from the displacement of conventional electricity production (assuming displacement of fossil fuels in the U.S. average grid mix of fuels for electricity production). The emissions data obtained for the gasification piece of the LCA exhibits a wide range of variation from a net savings of approximately 0.28 TCE/dry ton (~0.02 TCE/MMBtu energy produced) to a burden of 0.05 TCE/dry ton (~0.005 TCE/MMBtu energy produced) as illustrated by the minimum and the maximum bars.

Cost

Cost data were only available for one of the gasification technology vendors. **Figures 3-7 and 3-8** show the cost (or revenue) by process as well as the total net cost of approximately ($48) to ($12) per ton of MSW or ($3) to ($2) per MMBtu of energy produced. This signifies that the revenues received from the sale of electricity are greater than the costs to process the MSW via the gasification technology. In **Figures 3-7 and 3-8**, the process cost/revenue is per vendor-supplied values and the remaining residuals disposal costs are per RTI's MSW DST.

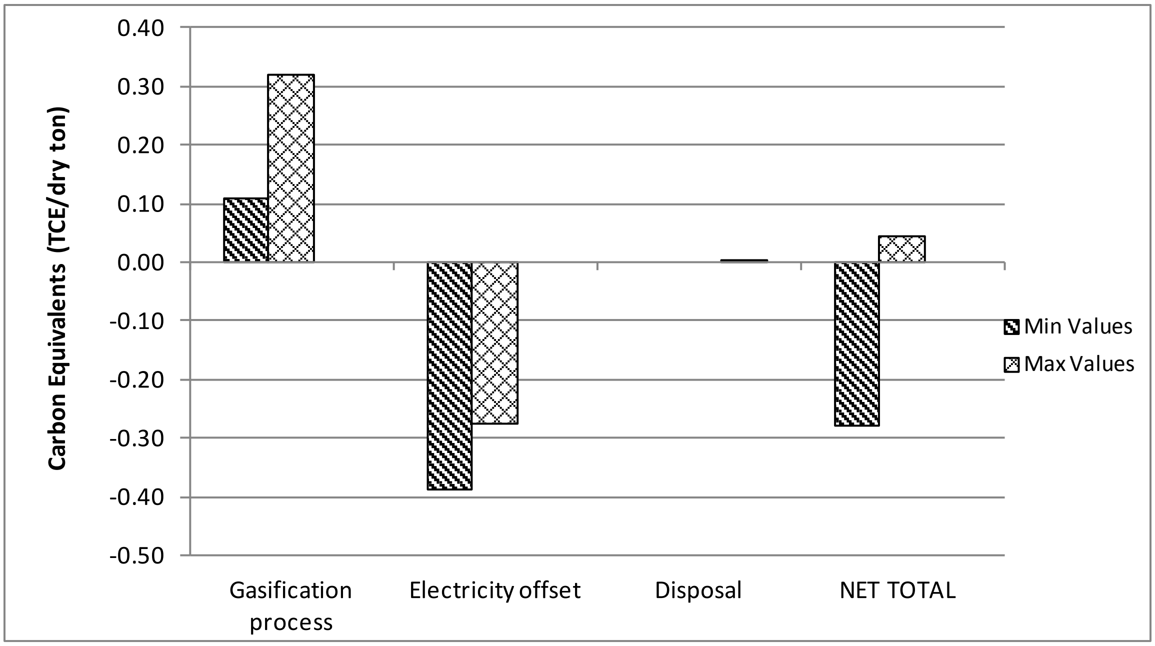

Figure 3-5. Net Carbon Equivalents Per Ton for Gasification of MSW.

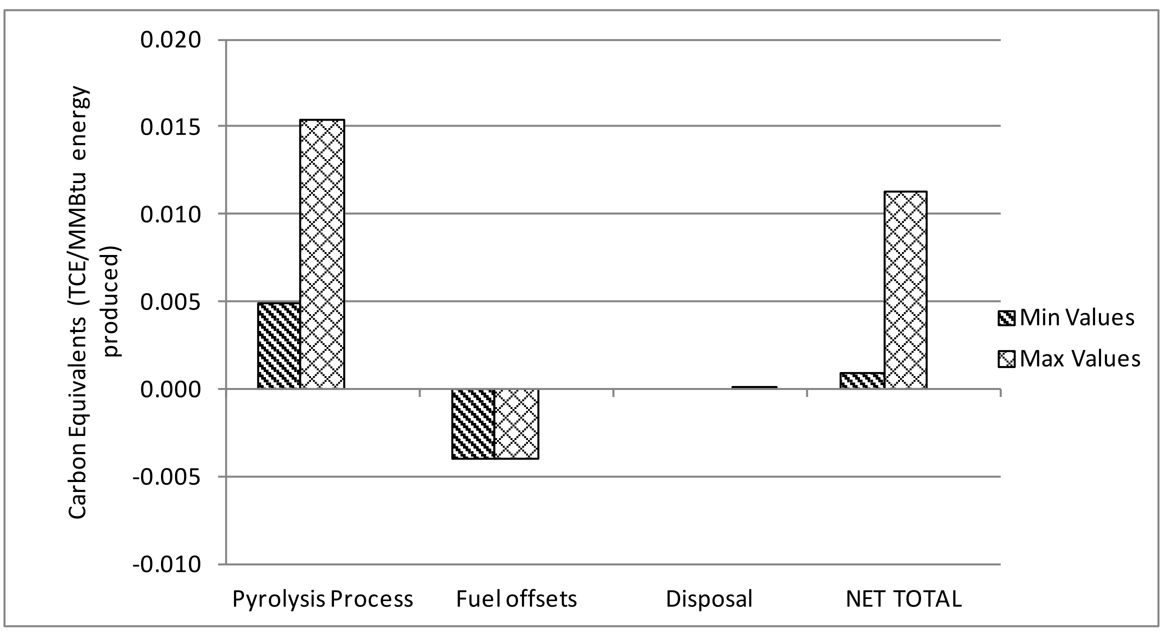

Figure 3-6. Net Carbon Equivalents Per MMBtu for Gasification of MSW.

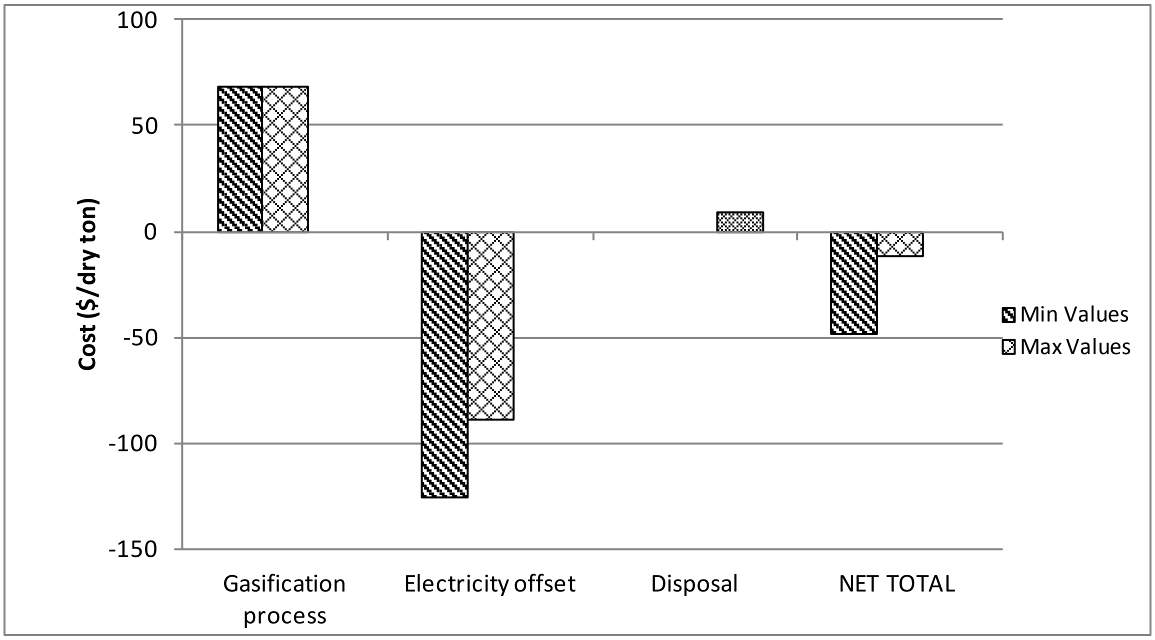

Figure 3-7. Net Cost Per Ton for Gasification of MSW.

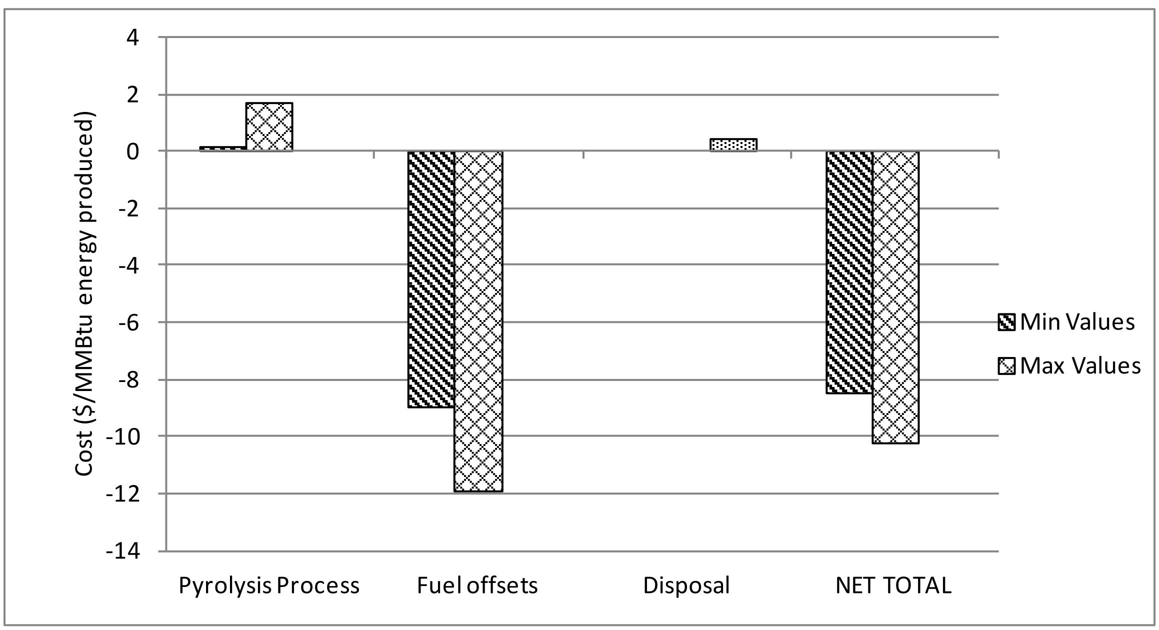

Figure 3-8. Net Cost per MMBtu for Gasification of MSW.

Comparison to Landfill and WTE Base Cases

The results for gasification of MSW were compared to results for a landfill and WTE base cases for MSW. A low–high range was developed for the landfill base case using a landfill with gas collection and flaring for the "low" end of the range and a landfill with gas collection and energy recovery for the "high" end of the range. The landfill base case was modeled using RTI's MSW DST and is representative of a U.S. average. For WTE, the lower end of the range represents facility with an efficiency of 18,000 btu/kwh and the upper end of the range represents facility with an efficiency of 14,000 btu/kwh. It is assumed that the electricity produced from WTE displaces electricity from utilities based on the U.S. average electricity grid mix of fuels.

Figure 3-9 shows the results for net energy consumption (i.e., energy consumed minus energy produced). According to this figure, the net energy saved using the gasification technology versus landfill disposal is approximately 6.5–13 MMBtu per dry ton of MSW. These savings are mostly associated with the energy produced by the gasification facility. For example, when compared to a landfill with energy recovery (i.e., the low landfill energy consumption bar in **Figure 3-9**), these savings indicate that the gasification facility is much more efficient at producing energy than the landfill facility. WTE also results in a net energy savings that appears to be at the high-end of the gasification savings. Gasification in general has the potential for energy savings on a per ton basis than WTE because it is designed to be a more efficient conversion process.

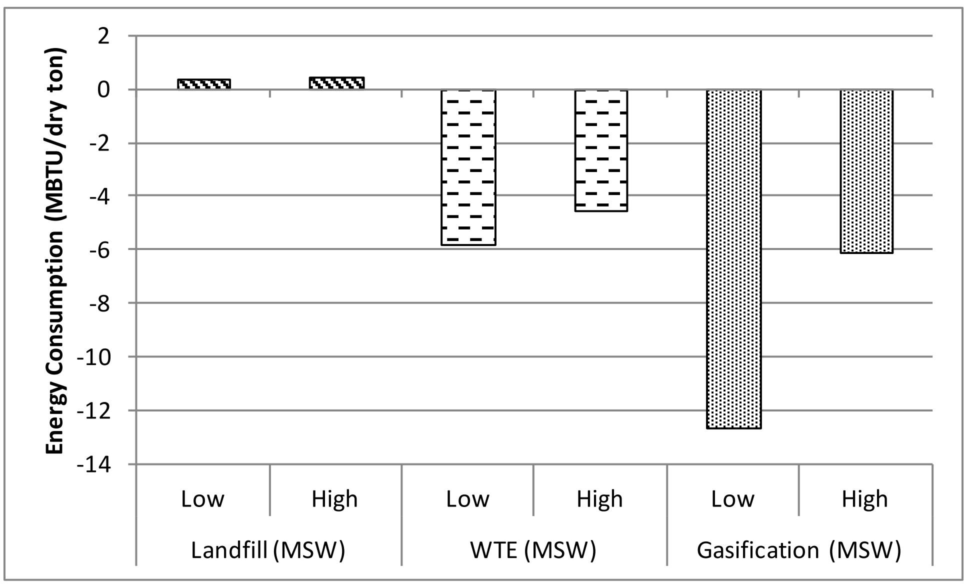

Figure 3-9. Net Energy Consumption for Landfill, WTE and Gasification of MSW.

Figure 3-10 shows the results for net carbon emissions (i.e., carbon emissions minus savings). According to this figure, the gasification technology results in a net reduction of approximately 0.3–0.6 TCE per dry ton of MSW processed when compared to landfills. This reduction is mostly associated with the energy produced by the gasification facility. For example, **Figure 3-9** indicates that the gasification facility is more efficient at energy production than the landfill with energy recovery, so the emissions savings associated with energy production using waste versus virgin materials are also greater for gasification facilities. Again, the WTE alternative also

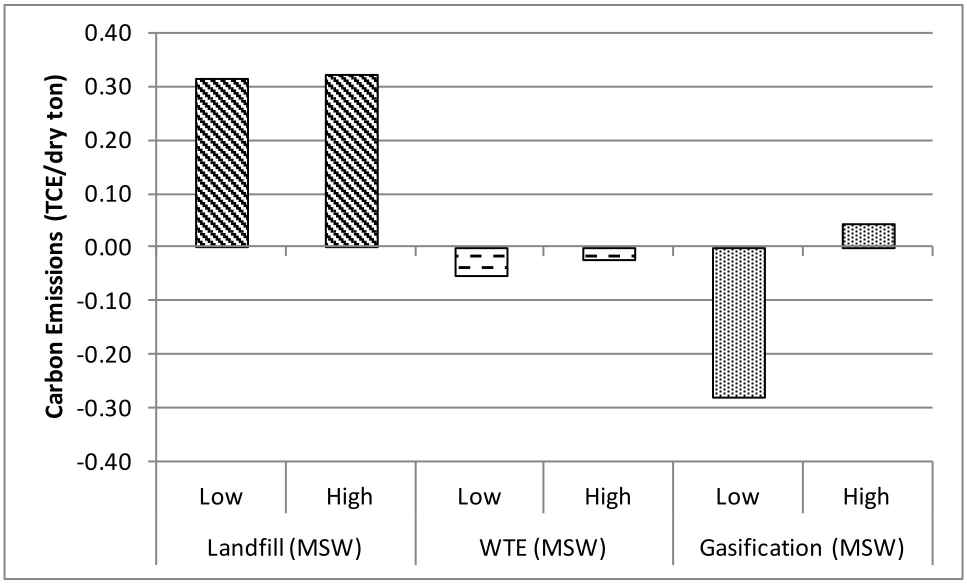

Figure 3-10. Net Carbon Equivalents for Landfill, WTE and Gasification of MSW.

results in a net carbon emissions savings that is in-range with gasification but potentially not as great due to the expected energy conversion efficiency of gasification.

Figure 3-11 shows the results for net cost (i.e., cost minus revenues). According to this figure, the gasification technology results appear to result in a net reduction of approximately $50–115 per dry ton of MSW processed when compared to landfills and will depend upon power pricing as well as the cost to build, finance, and operate. By having larger energy savings, as illustrated in **Figure 3-9**, the gasification facility will also get more revenues from energy sales than the landfill with energy recovery. Consistent with the energy and GHG emissions results, this reduction is mostly associated with the energy produced by the gasification facility and the stated cost of operation by technology vendors. WTE by contrast has a significantly higher cost than gasification, based on the available data. In general, higher quality data from gasification technologies is needed to better characterize costs. It's not clear if currently available cost estimates include all costs and are accurate, as there are no currently stand-alone commercially operating facilities that were found.

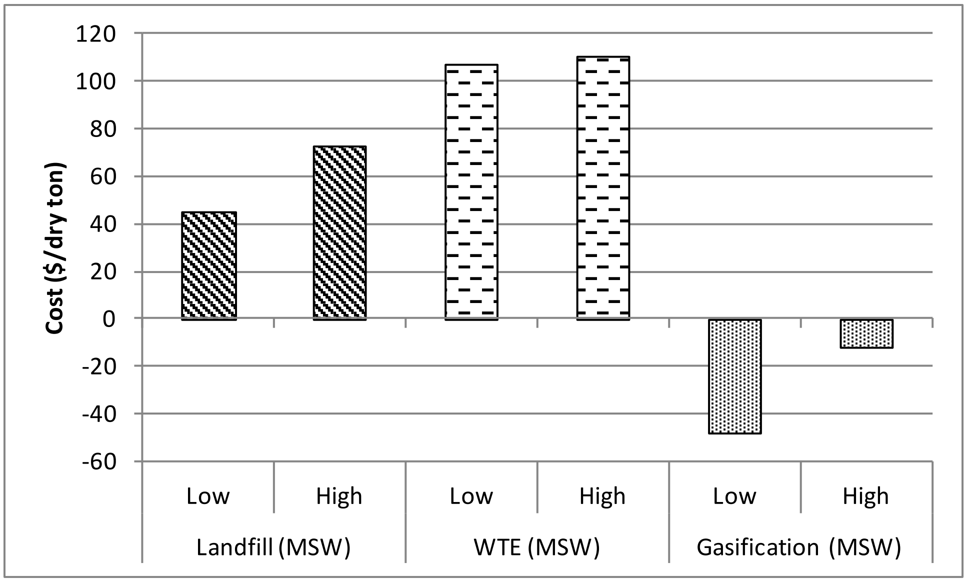

Figure 3-11. Net Cost for Landfill, WTE and Gasification of MSW.

Section 4:
Anaerobic Digestion Technology

AD is a biochemical conversion process that decomposes organic material in the absence of oxygen (O_2). Organic waste materials such as manure, agricultural wastes, and biodegradable fractions of industrial, commercial, and MSW (or fractions of MSW) can be used as feedstocks for anaerobic digesters. The main product of AD is a methane-rich biogas, which can be combusted to generate heat and/or electricity, converted to pipeline quality gas, or further refined to create biomethane, a transportation fuel. Byproducts of AD include CO_2 and undigested solids. Depending on the type of feedstock used, the undigested solids may have economic value when refined and used as a fertilizer soil amendment.

There are several types of anaerobic digesters. Digesters can be classified into "wet" or "dry" systems, depending on the feedstock; into single- or multiple-stage systems, depending on their complexity; and batch or continuous flow systems, depending on the feedstock input method.

- ***"Wet" or "dry" systems***—Wet systems generally process feedstocks with a total solid content of less than 15 percent, whereas dry systems process feedstocks with greater than 15 percent total solid content. Wet systems are most appropriate for wastewater AD. Dry systems are preferred for MSW because bacteria have a higher survival rate and less pre-handling is required.

- ***Single-stage or multiple-stage systems***—Multi-stage systems are more expensive than single-stage systems to construct and operate; however, they have higher loading rates and greater feedstock flexibility. For MSW, the majority of AD systems are single-stage due to the complexity and cost barriers of multi-stage systems, but the prevalence may change as technology becomes more affordable and standardized.

- ***Batch or continuous flow systems***—Batch systems process waste within a single sealed reactor or holding tank, whereas continuous systems use a series of reactors. Batch systems require less precision and have lower construction costs than continuous systems, but may result in inconsistent biogas production and incomplete degradations. Comparatively, continuous systems increase process efficiency due to increased control over bacterial reactions taking place within the reactors.

Some pre-sorting and pretreatment is necessary to limit the clogging of the pumps and to reduce inert material(s) located in the reactor. Also, it is necessary to remove metals and plastics prior to adding the stream into the AD. Otherwise, the stream may contaminate the process. Generally, the material handling systems include extensive receiving, particle size reduction, and separation processes before the feedstock may be fed into the digester.

4.1 Example Anaerobic Digestion Facilities

Existing AD facilities identified in North America are listed in **Table 4-1**. As shown in the table, the vendor name, status, accepted feedstock, location and main product output are listed. AD for MSW is being used in Europe[6]. However, few commercial AD facilities that process MSW are in operation in the United States. A pilot facility, East Bay Municipal Utility District, is currently operating in California. It co-digests food scraps from restaurants within the San Francisco Bay area at its wastewater treatment plant in order to generate biogas that is used to produce electricity. The study has found that converting 100 tons per day (TPD) for five days per week offers enough power for 800–1,400 homes annually. Another private AD facility built by Clean World recently opened at American River Packaging. As shown in **Table 4-1**, there are a number of AD facilities currently under development. Each of these facilities produces biogas as the main product which is typically used for producing electrical energy. Peat is a byproduct from AD technology that may be marketable as compost.

4.1.1 County of Yolo Public Works Department: Yolo County, California

This project is not a conventional AD project in that the digester unit was constructed as a cell on top of an existing landfill cell as it will be described in detail under the **Process Details** section. The California Department of Resources Recycling and Recovery (CalRecycle) commissioned the design and construction of this pilot-scale anaerobic digester. The system is co-located at Yolo County Central Landfill and has been in operation since 2007. This system takes advantage of the facility's landfill gas-to-energy infrastructure to increase the energy recovery efficiency of the digester and also allows for the recovery of the residual material to be used as compost. Due to the innovations in the project, this AD approach has the potential to be more cost-effective at a larger scale than many other AD systems (CalRecycle, 2010) when compared with landfill disposal and other waste management techniques.

The digester was constructed on top of an existing landfill cell. The digester cell was lined and then layered with 1,894 tons of green waste, 34 tons of wood chips, 130 tons of aged horse manure, and 25 pounds of limestone and capped with a liner cover. Pipes that are distributed between the waste layers transfer the gas to the energy facility located onsite. Leachate and water are re-circulated to promote anaerobic degradation.

The process has demonstrated the ability to produce 1,680 cubic feet of methane per dry ton of waste. Due to these results, it was suggested that further pilot projects be initialized in order to understand the technological barriers such as high moisture waste and odor issues associated with food waste. It is also recommended that a better quantification of emissions associated with composting be assessed. Overall, the study found that California would greatly benefit from a wider implementation of waste diversion to produce methane gas and electricity.

[6] See http://www.seas.columbia.edu/earth/vermathesis.pdf for a listing of AD facilities in Europe.

Table 4-1. AD Technology Facilities in North America.

Vendor Name	Status	Feedstock	Location	Main Product	Source (Sites accessed in June 2012)
Clean World	Commercial	Food, paper and agricultural residue	Sacramento, CA	Biogas	http://www.cleanworldpartners.com/technologies/
City of Riverside	Commercial	grease from restaurants	City of Riverside	Biogas	http://www.riversideca.gov/sewer/project-grease.asp
Quasar Energy Group	Commercial	MSW components, crop waste, grass, and manure	Wooster, OH	Electricity	http://www.schmackbioenergy.com/pages/wooster.html
Quasar Energy Group	Commercial	MSW components	Columbus, OH	Electricity, biogas, and CNG	http://www.schmackbioenergy.com/pages/columbus.html
Central Marin Sanitation	Commissioned	MSW components	City of San Rafael	Biogas	http://www.cityofsanrafael.org/Assets/Methane+Gas+Study.pdf
Humboldt Co. Waste Authority	Commissioned	grease from restaurants	Humboldt Co. Waste Authority	Biogas	http://www.hwma.net/HRFWDFS.pdf
Terrabon	Demo	MSW, sewage sludge, forest/ag residues	Bryan, TX	Gasoline	http://www.terrabon.com/mixalco_semiworksplant.php
B & D Geerts	Demo	Food waste, green material, and mixed solid waste	Yolo County, CA	Biogas	http://www.epa.gov/region9/organics/symposium/2010/Pors9-15-10.pdf
East Bay Municipal Utility District	Demo	MSW components	East Bay Municipal Utility District	Biogas	http://www.epa.gov/region9/organics/symposium/2010/Pors9-15-10.pdf
Sacramento Co. Regional WWTP	Demo	MSW components	Elk Grove, CA	Biogas	http://www.biomassmagazine.com/articles/3376/building-on-its--biomass-base/
Arrow Ecological	Permitted	MSW components	Perris, CA	Electricity	http://dpw.lacounty.gov/prg/pressroom/printview.aspx?ID=370&newstype=PRESS

4.1.2 Quasar: Wooster, Ohio

Quasar joined Ohio State University's Agricultural Research and Development Center (OARDC) to build an AD system called the ecoFARMsystem550 (F550) system in the BioHio Research Park located in Wooster, Ohio. The F550 system uses regional food and crop waste as well as grass and manure from the university's farm operations in order to produce renewable energy and other byproducts.

In the Quasar process, a receiving hopper is filled with biomass within the plant building to control odors. Live bottom hopper augers move the waste toward the middle of the hopper. Biomass is discharged and passes through a grinder to the process lines. Fresh biomass mixes with heated recycled biomass and moves into the biomass equalization tank. The liquid waste passes through a strainer in order to remove any leftover solid materials. Liquid biomass is then added to the equalization tank, which may store biomass for up to six days. A pipe connects the head space in the equalization tank with the digester tank and dual purpose tank in order to sustain equalized pressure. The space also provides an area for displaced gas from filling or discharging or temperature expansion.

After digestion is complete, the biomass is pasteurized in order to remove pathogens. Energy recovery is completed through a biomass to biomass heat exchanger as it is pumped to a holding tank. Energy recovered is transferred and temperature elevated through a heat exchanger. Suspended solids in the digested material are mechanically separated in a dewatering process. The resulting cake biomass is about 25 percent dry solids.

The system capacity is 550,000 gallons, and biomass may be stored for about 3 days, while the average digestion time is about 28 days. The system can handle 19,382 wet tons of waste annually, and produces 5,256 MWh of electricity. The digester is currently operational and is able to offset half of OARDC's electricity demand.

4.1.3 Clean World/American River Packaging-Sacramento, CA

Clean World Partners recently opened a commercial high-solids AD system at American River Packaging's Sacramento headquarters. The Clean World AD system is based on AD technology developed at the University of California, Davis and is designed to convert food waste, agricultural residue, and other organic waste into renewable energy, fertilizer and soil enhancements. Clean World anticipates that its AD technology installed at American River Packaging will convert 7.5 tons of food waste from Campbell Soup and other regional food producers along with .5 tons of unrecyclable corrugated material into biogas. Clean World claims the biogas produced will generate approximately 1,300 kWh of renewable electricity per day, supplying about 37 percent of American River's internal electricity needs.

Clean World's process can be classified as "dry" and multi-stage. The vendor materials claim organic solid waste with up to 50 percent solid content can be accepted without adding water. With relatively homogeneous organics coming from industrial/commercial partners, additional preprocessing of the organics is said to be minimized. Clean World claims that the high-solids technology is more efficient and flexible than other existing AD systems and rapid waste throughput will require less water for processing, reduce tank size and manufacturing costs.

The Clean World system installed at American River Packaging resulted from a public-private partnership. Research and feasibility studies were provided by UC Davis, CalRecycle and the California Energy Commission. Private investment funded the facility's construction and installation. Being privately owned and operated, it appears that the facility accept organics only from contracted industrial/commercial partners. The vendor estimates that more than 2,900 tons of organic waste will be diverted annually from landfills, and that the AD technology will produce 1,000 tons of organic soil amendment per year for application at regional agricultural sites. According to Clean World, the solid byproduct is considered to be wastewater by California regulations and it's treated via a membrane separation system to create a higher-value product that is currently sold for agricultural application. It's unclear at this time whether this product will offset the use of fertilizers or other products at the application site.

No emissions or cost information was found for the Clean World facility at American River Packaging. A report from the California Energy Commission with this type of information is expected to be released in mid- to late-2012. Clean World is also constructing a planned 100-ton per day AD system in south Sacramento which is expected to open in late spring 2013.

4.2 Environmental Data and LCA Results

For this study, RTI developed ranges for energy and emissions data for the AD technology category as a whole, as shown in **Table 4-2**. We were not able to identify data available for stand-alone commercial AD facilities, and therefore data was developed from existing studies in the open literature. An assessment report is planned for release for the Clean World AD facility at American River Packaging but it was not available at the time of this report.

LCA results for energy consumption and GHG emissions (as carbon equivalent emissions), as well as cost are presented and discussed in this section of the report. Results are presented as net total burdens minus benefits. Therefore, negative energy results mean that more energy is recovered than that needed to run the processes; negative GHG emissions mean that there are more emissions savings as a result of energy and fuels production using the waste material relative to using virgin material; and negative cost results mean that the revenues are higher than the costs.

The cost and LCA results for energy and GHG emissions for AD of organics (namely, food and yard wastes) are presented in this section. AD results include transportation and disposal of residuals. Thus the cost and LCA results include the burdens associated with the AD facility as well as with transportation and disposal of residuals. The benefits are those associated with energy recovery. With AD technology, the resulting peat/compost byproduct may also be used as a soil amendment but it is difficult at this time to know what, if any, other products (e.g., fertilizers) may be displaced. For purposes of the LCA, it was assumed that the peat/compost byproduct would not offset other products.

The key data and assumptions for the LCA and those specific to AD are included in **Attachment A**. Consistent with the LCA results for pyrolysis and gasification, the LCA results for AD are presented as net totals, burdens minus benefits.

Table 4-2. AD Process Data Per Dry Ton of Input Material.

Parameters		Units	Value			Data Sources
Process Characteristics						
Power consumption/parasitic load		% energy produced	22	-	30	RTI (2005) and ARI (2007)
Total Solids		%			70	RTI (2005)
Volatile Solids		%			70	RTI (2005)
Biodegradable Volatile Solids		%			75	RTI (2005)
Conversion Efficiency waste to methane		%	60	-	75	RTI (2005) and ARI (2007)
Conversion Efficiency methane to electricity		%	33	-	39	RTI (2005) and ARI (2007)
Air Emissions Data						
PM		lb			0.12	RTI (2005)
HCl		lb			0.02	RTI (2005)
Nitrogen Oxides		lb			0.61	RTI (2005)
Sulfur Oxides		lb			0.03	RTI (2005)
Carbon Monoxide (CO)		lb			1.15	RTI (2005)
Carbon Dioxide (biomass)		lb			137	RTI (2005)
Cost Data						
Cost per design capacity		$/dtpd			82	ARI (2007)

Energy

For AD, energy is consumed in feedstock pre-processing, digestate post processing, ancillary systems, and transport and dispose of residuals in a landfill. Energy in the form of methane-rich biogas, which can be combusted to generate heat and/or electricity or further refined to create biomethane, a transportation fuel, is the main output from the AD process. For this analysis we assumed the biomethane will be used to generate electricity.

The LCA results for energy consumption for AD are shown in **Figures 4-1 and 4-2**. According to **Figure 4-1**, the electricity output generates energy offsets. The AD process can be considered an energy producer (i.e., the energy produced exceeds the energy consumed), with some variation in the amount of energy produced, according to the data obtained from the literature.

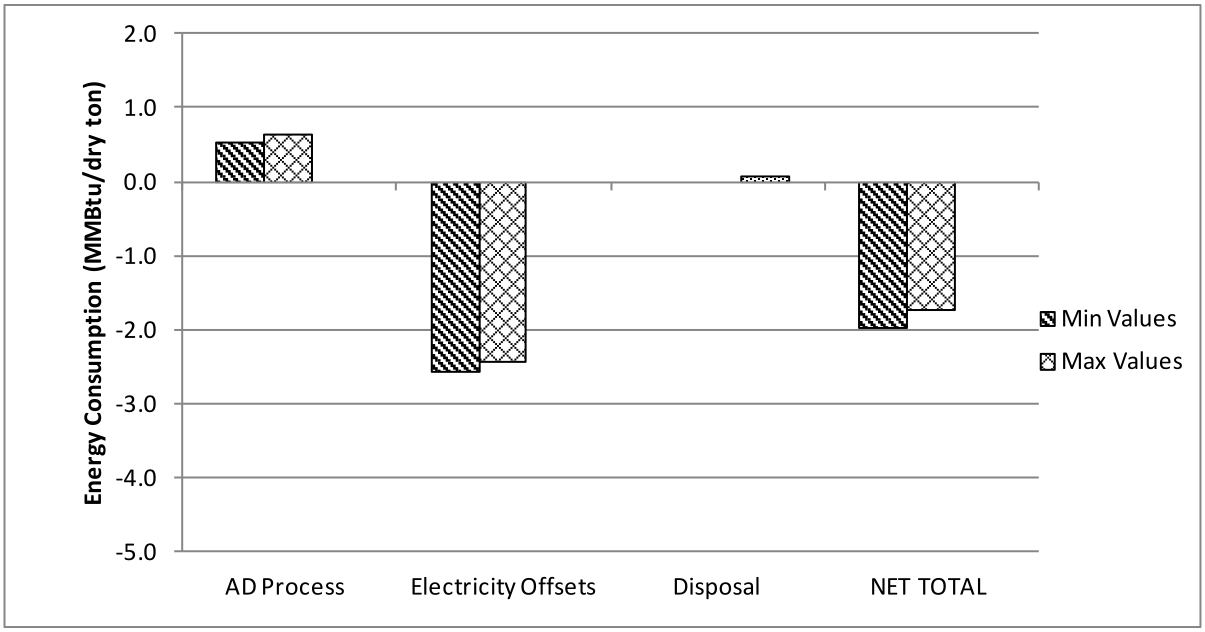

Figure 4-1. Net Energy Consumption Per Ton for AD of Organics.

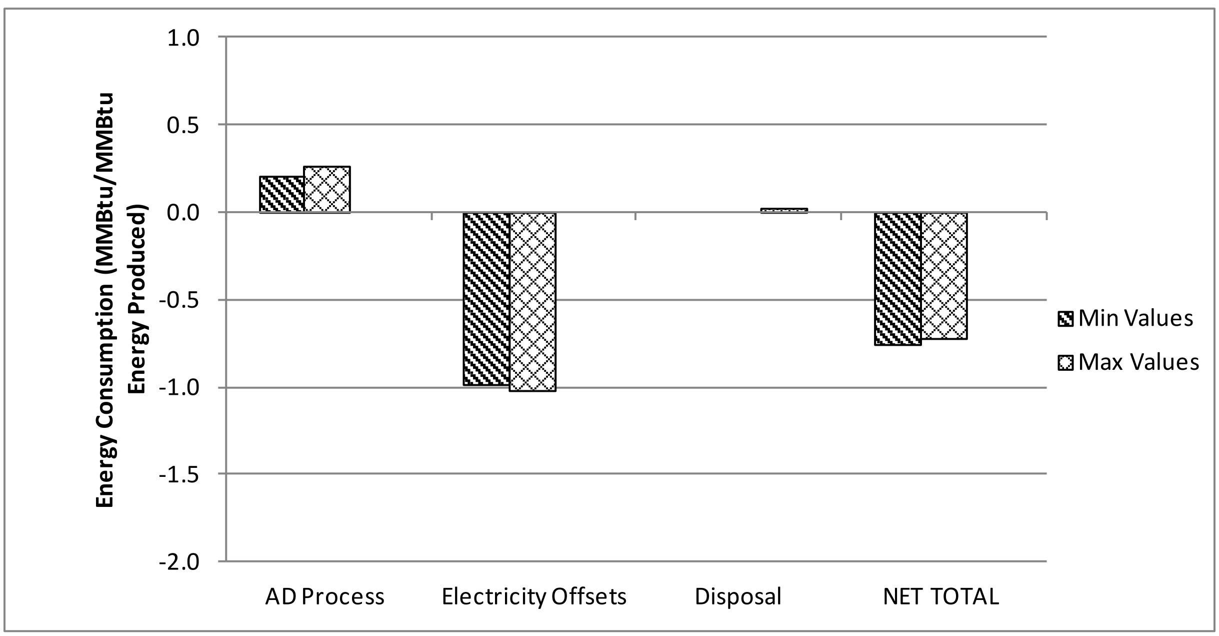

Figure 4-2. Net Energy Consumption Per MMBtu for AD of Organics.

GHG Emissions

Consistent with the energy results, **Figures 4-3 and 4-4** show that the AD of organics results in GHG emissions savings, which results from the displacement of conventional electricity production (assuming displacement of fossil fuels in the U.S. average grid mix of fuels for electricity production).

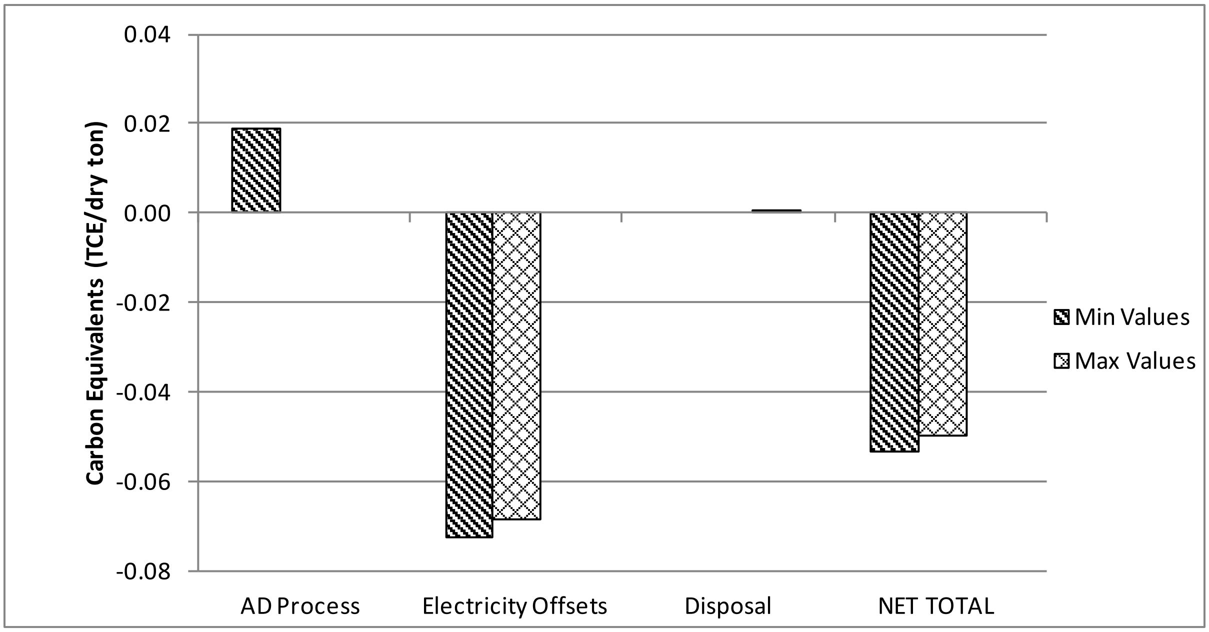

Figure 4-3. Net Carbon Equivalents Per Ton for AD of Organics.

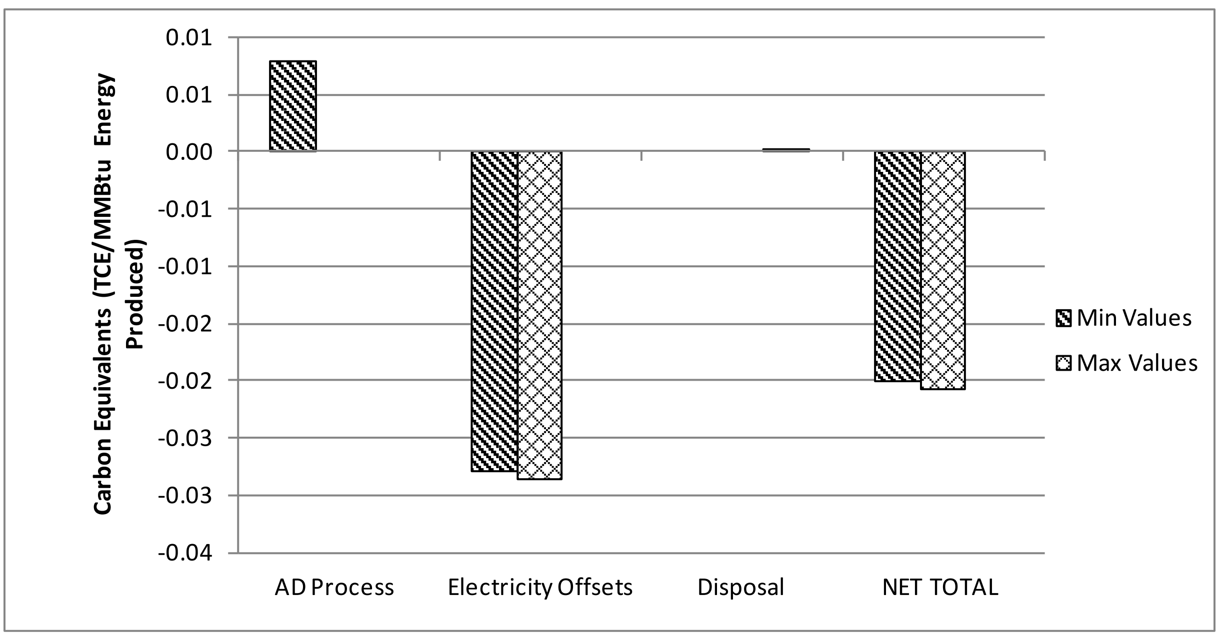

Figure 4-4. Net Carbon Equivalents Per MMBtu for AD of Organics.

Cost

The net (expenses–revenue) cost per ton for the AD of organics is shown in **Figures 4-5 and 4-6**. As shown in these figures, the net cost range is positive, signifying a net cost stream that results

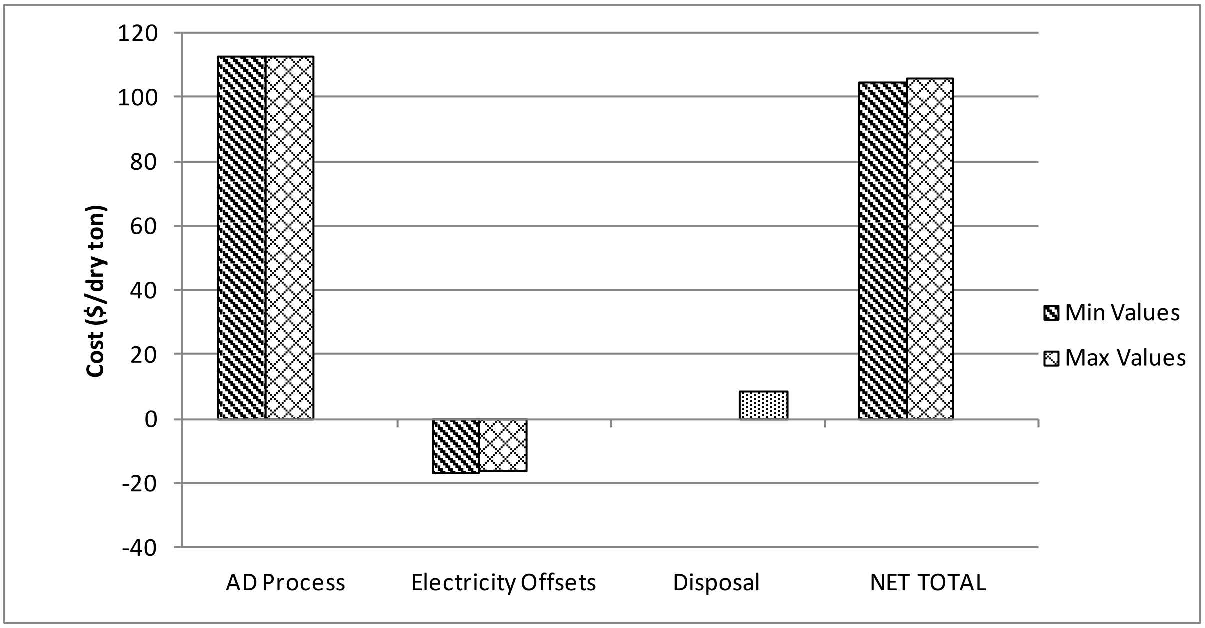

Figure 4-5. Net Cost Per Ton for AD of Organics.

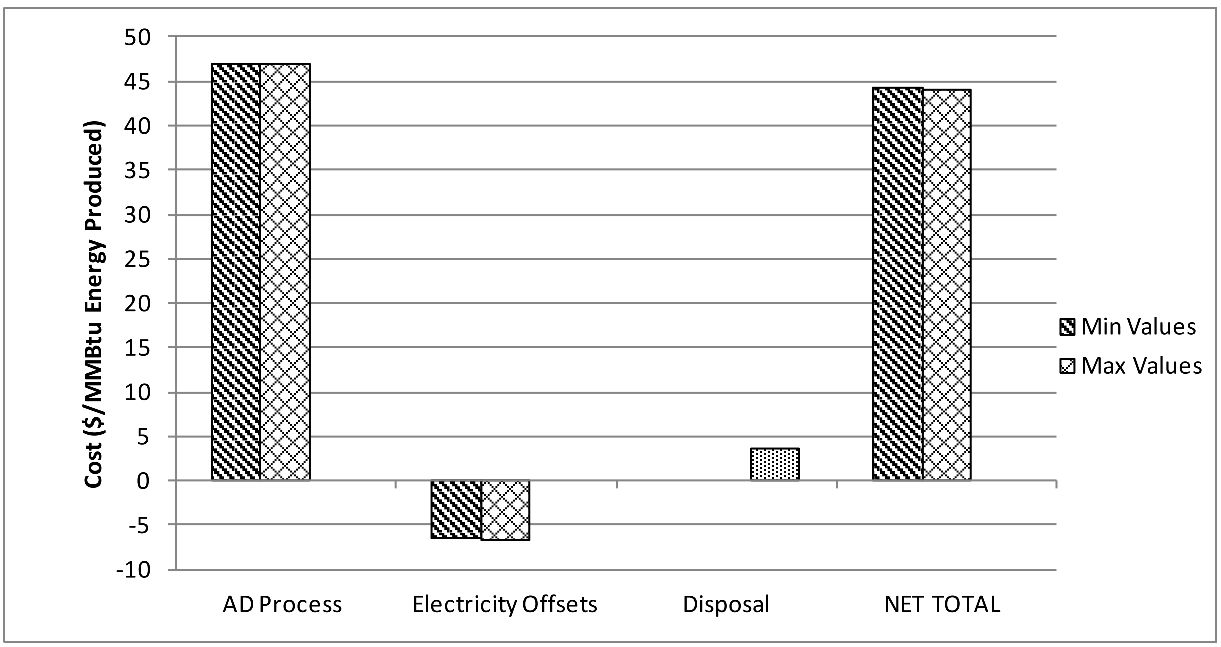

Figure 4-6. Net Cost Per MMBtu for AD of Organics.

from the capital and operating costs of AD being greater than the revenues brought by electricity sale.

Comparison to Landfill and WTE Base Cases

In this section, the results for the AD of organics are compared to results for a landfill and WTE base cases for organics. A low–high range was developed for the landfill base case using a landfill with gas collection and flaring for the low end of the range and a landfill with gas collection and energy recovery for the high end of the range. The landfill base case was modeled using RTI's MSW DST and is representative of a U.S. average. For WTE, the lower end of the range represents facility with an efficiency of 18,000 btu/kwh and the upper end of the range represents facility with an efficiency of 14,000 btu/kwh. It is assumed that the electricity produced from WTE displaces electricity from utilities based on the U.S. average electricity grid mix of fuels

Figure 4-7 shows the results for net energy consumption (i.e., energy consumed minus energy produced). According to this figure, the net energy saved using the AD technology versus landfill disposal is approximately 0.6–2.5 MMBtu per dry ton of organics. These savings are mostly associated with the energy produced by the AD facility. For example, when compared to a landfill with energy recovery (i.e., the low landfill energy consumption bar in **Figure 4-7**), these savings indicate that the AD facility is more efficient at producing energy than the landfill facility. However, when compared to WTE the AD technology does not appear to be as efficient in converting organics to energy.

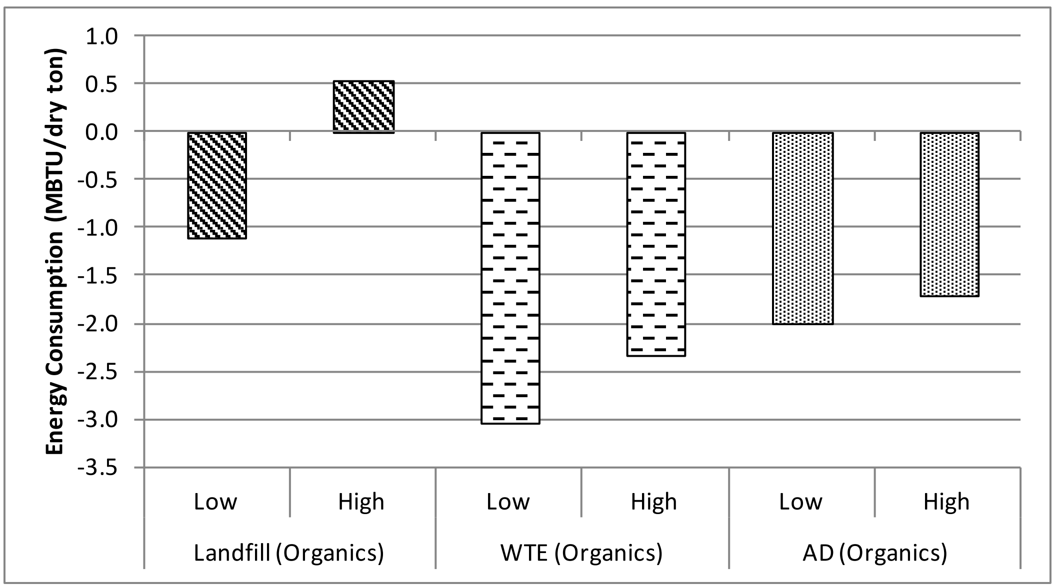

Figure 4-7. Net Energy Consumption for Landfill, WTE and AD of Organics.

Figure 4-8 shows the results for net carbon emissions (i.e., carbon emissions minus savings). According to this figure, the AD technology results in a net reduction of approximately 0.11–0.13 TCE per dry ton of organics managed via AD as compared to landfill disposal. This reduction is mostly associated with the energy produced by the AD facility. For example, **Figure 4-7** indicates that the AD facility is more efficient at energy production than the landfill with energy recovery, so the emissions savings associated with energy production using waste

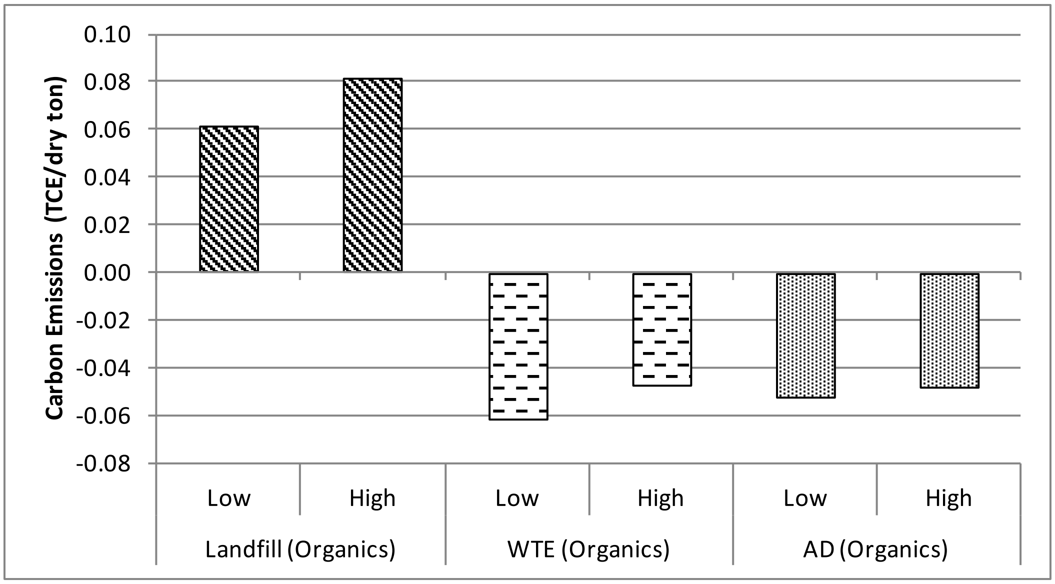

Figure 4-8. Net Carbon Equivalents for Landfill, WTE and AD of Organics.

versus virgin materials are also greater for AD facilities. WTE appears to result in the same level of net carbon emission reduction as AD.

Figure 4-9 shows the results for net costs (i.e., costs minus revenues). According to this figure, the AD technology results in a net reduction of approximately $75 per dry ton of organics processed when compared to landfills. Consistent with the energy and GHG emissions results, this reduction is mostly associated with the energy produced by the AD facility. For example, by having larger energy savings, as illustrated in **Figure 4-7**, the AD facility will also get more revenues from energy sales than the landfill with energy recovery. AD also appears to be slightly higher in net cost as compared to WTE.

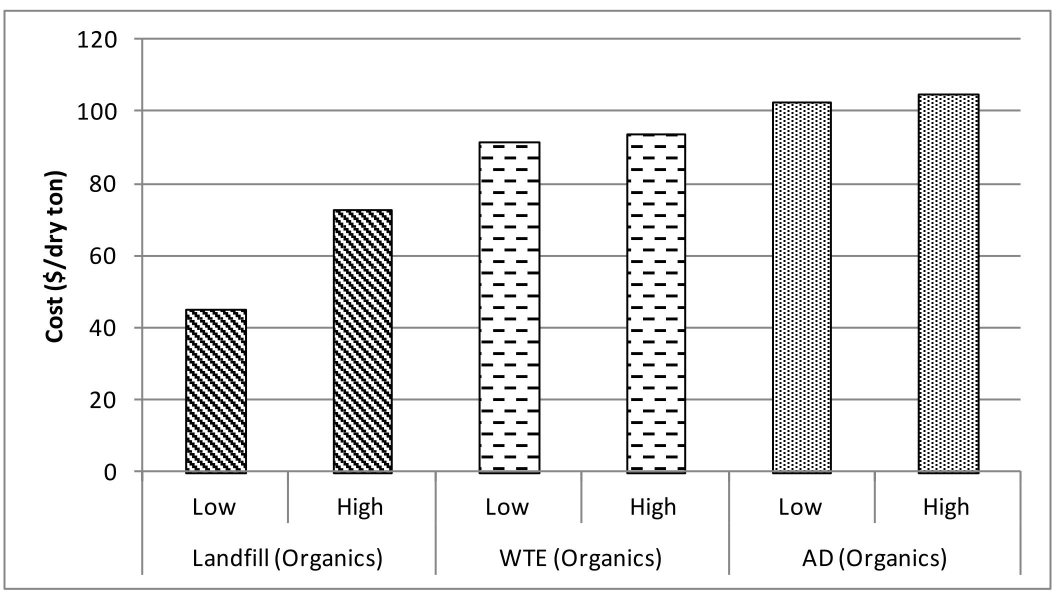

Figure 4-9. Net Cost for Landfill, WTE and AD of Organics.

Section 5: Findings and Recommendations

Emerging waste conversion technologies may present alternatives to landfill disposal for managing non-recycled MSW; however, there are currently very few commercially operating facilities in the U.S. At the time of this study, we estimated there were 9 pyrolysis, 7 gasification, and 10 AD demonstration and commercially operating facilities in North America[7] that process municipal wastes. In general, we found that plastics-to-oil pyrolysis facilities were at a more mature commercially operating stage in the U.S., while bulk MSW (typically gasification) and organics (typically AD) technologies were still largely in the demonstration phase at the time of this report.

Anecdotal evidence suggests that project viability may in part be affected by difficulties encountered scaling up facilities from demonstration to commercial scale (especially MSW-based plants), financial backing/economic conditions, and the highly variable permitting classifications. In addition, having a [contractually and compositionally] dedicated and/or segregated feedstock is another challenge to successful commercialization.

5.1 Key Findings

The following sections highlight our key findings from this study including current waste conversion facilities in the U.S. exhibit:

- Significant differences in accepted waste materials.
- Considerable variation among technology vendor processes.
- Potential environmental benefits by virtue of energy and materials recovery.
- Potential cost competitiveness with conventional waste management technology.
- High-level of uncertainty surrounding existing environmental and cost performance data.

Each of these findings is expanded on in the following sections.

5.1.1 Significant Differences in Accepted Waste Materials

Ultimately, the findings from this research show that the different categories of waste conversion technologies are designed to handle very different types of waste feedstock. In general, pyrolysis technologies utilize only plastics, gasification technologies utilize MSW, and AD utilizes food, yard, and paper waste. Pyrolysis facilities were reported to receive plastics from both materials recycling facilities and, more so, from industrial partnerships. Gasification can received bulk MSW (pre- or post-recycling) but requires up-front sorting and processing to remove undesirable materials. Alternatively, a gasification facility could partner with a MRF to receive positive-sort materials that are desirable. For AD, the food, yard, and residual paper fractions of MSW will need to separated out, either at the source or up-front of the AD facility. Similar to pyrolysis, it may be advantageous for AD facilities to secure industrial/commercial partners for feedstock (as is being done with the Clean World/American River Packaging facility).

[7] This includes demonstration and commercial scale facilities only. Proposed and planned facilities were not included.

It is also difficult to compare the cost and performance of pyrolysis, gasification, and AD technologies directly due to differences in feedstock. Differences in accepted feedstock means there will create differences in feedstock energy value as well differences in beneficial offsets. For pyrolysis, beneficial offsets are primarily based on the conversion of plastics to oil. For gasification, beneficial offsets include energy production and can also include the recyclables (e.g., remove metals, glass, and other inorganics) in the up-front sorting process but this component was not included in this analysis since we assumed non-recycled waste would be the input feedstock and little recyclables available. For AD, the benefit offsets are primarily based on the conversion of organic wastes to biogas which is assumed to be used to produce electrical energy.

5.1.2 Considerable Variation among Technology Vendor Processes

Within the main technology categories of pyrolysis, gasification and AD, different technology vendors/facilities have specific variations on the process to enhance conversion efficiency and/or tailor the end product to their respective site-specific markets. The primary objective of the conversion technologies is to convert waste into useful energy products that can include syngas or biogas, petroleum, and/or commodity chemicals. Syngas and biogas can be used directly in industrial boilers or in an ICE gen-set to produce electrical energy. Petroleum and commodity chemicals are typically tailored to specific end-users (e.g., petroleum wax for cosmetics manufacturers). Each end product has different life-cycle offsets which may affect the overall environmental impact of the process.

While studies and analyses can be done on waste conversion technologies in general (as done in this report), specific analyses also need to be done for individual technologies located in specific regions. In this regard, all technologies have their benefits (and burdens) and decisions about their adoption will likely be done on a site- or region-specific basis and depend on characteristics such as waste composition, contracts for assuring steady waste feedstock supply, State and local permitting conditions, market prices for electricity and fuels, availability of markets for products, and distance to those markets.

5.1.3 Potential Environmental Benefits by Virtue of Energy and Materials Recovery

Using the currently available data, a high-level LCA conducted for the conversion technologies indicates that the technologies may offer environmental benefits as compared to landfill disposal. Specifically, we estimated that gasification (excluding energy production and materials recycling offsets) of MSW saves between 6.5—13 MMBtu per ton as compared to landfill disposal. Pyrolysis of waste plastics saves between 22—32 MMBtu per ton as compared to landfill disposal. Likewise, our results show that gasification of MSW saves between 0.3—0.6 TCE emissions per ton of MSW treated as compared to landfill disposal. Pyrolysis of waste plastics saves between 0.03 and 0.26 TCE emissions per ton as compared to landfill disposal. AD of organics waste saves between 0.11—0.13 TCE per ton compared to landfill disposal.

Given the developmental stage and the current capacities of technologies, our preliminary estimates suggest that conversion technologies would offset significantly less than 1 percent of total annual U.S. oil consumption. For example, the average size of a plastics-to-oil facility is in the range of 10–30 tons per day. If there were 100 plastics-to-oil facilities in the U.S. by 2015, conversion production could offset approximately 6,000–18,000 barrels of oil per day, assuming

1 ton of plastic is equivalent to 6 barrels of oil. Total consumption of oil in the U.S. is forecast to be 21.57 million barrels per day in 2015.[8] Therefore, according to these estimates, 100 commercial-scale plants would supply, at most, a tenth of 1 percent of U.S. oil consumption. While MSW-based conversion facilities are anticipated to convert 7–10 times more waste to energy, estimates still indicate significantly less than 1 percent of annual U.S. oil consumption.

From a local perspective, conversion technologies may show more pronounced benefits, including reduced energy and carbon emissions. When compared to landfill disposal, gasification of 100 tons of MSW per day and operating 300 days of the year may save energy equivalent to the needs of about 1805-3610 households, or 1480-2950 household transportation energy needs according to EPA information[9] about average household and household transportation energy needs. This translates into a reduction of approximately 33,000-66,000 tons of CO_2 emissions per year. Pyrolysis of 100 tons per day of non-recycled plastics may save the amount of energy equivalent to the needs of 555-1110 households, or 455-910 household transportation energy needs and about 16,500-27,500 tons of CO_2 emissions reduction per year. Treatment of 100 tons of organics waste in an AD facility may save the amount of energy equivalent to the needs of 167-694 households, or136-568 household transportation energy needs and approximately 12,100-14,300 tons of CO_2 emissions reduction per year.

5.1.4 Potential Cost Competitiveness with Conventional Waste Management Technologies

Estimates of cost provided by technology vendors indicate cost/ton may be comparable to other MSW options, such as recycling and landfilling. Vendors estimate that the cost to process the waste is approximately $50/ton for pyrolysis and gasification technologies, and approximately $100/ton for AD. This cost is generally related to the capital and operating costs required to run the process and the market price for products. For comparison, the U.S. average tipping fee is $44/ton for landfills and approximately $68/ton for mass burn WTE.[10]

The limited cost information available from the literature indicates that the cost/ton for pyrolysis is comparable to MSW options, such as recycling and landfilling, and that the cost/ton for gasification and AD is higher. The estimated waste processing cost for pyrolysis is approximately $50/ton of plastics, close to $90/ton of MSW for gasification, and close to $115/ton of organics for AD. This cost is generally related to the capital and operating costs required to run the process and dispose of any residuals. For comparison, U.S. landfill tipping fees range from $15–96/ton of MSW and WTE tipping fees range from $25–98/ton of MSW, depending on the State or region (Van Haaren et al., 2010).

The economic sustainability of conversion facilities will depend on the markets for energy and commodity products. Each facility will likely tailor its process to match site-specific market conditions and contractual arrangements. For example, according to common behavior if the price of crude oil continues to increase, technologies that convert plastics and MSW to

[8] http://www.researchandmarkets.com/research/96a49e/united_states_oil_and_gas_report_q1_2011.
[9] http://www.epa.gov/dced/location_efficiency_BTU-chtl-graph.htm
[10] http://www.seas.columbia.edu/earth/wtert/sofos/SOG2010.pdf

synthetic petroleum and/or liquid transportation fuels will be able to generate more revenue from the sale of products and become more cost competitive.

5.1.5 High-Level of Uncertainty Surrounding Existing Environmental and Cost Performance Data for Environmental and Cost Information

There is a high level of uncertainty associated with the current environmental and cost data associated with waste conversion technologies. Because most conversion facilities are demonstration plants, they are operating in batch-test mode and not as a continuous-mode commercial plant. Until there are commercially operating facilities in North America, there will not be good real-world data to characterize the environmental aspects and costs for these technologies. It was found that even facilities that are commercial-scale are often operating in more of a demonstration mode and do not have waste contracts and/or energy or product contracts in place.

5.2 Limitations and Recommendations for Future Research

Real-world cost and environmental information is difficult to obtain, due primarily to the current stage of development of conversion technologies in the U.S. As more commercial-scale facilities are built and operating, it would be beneficial to reassess the cost and environmental performance of conversion technologies as compared to competing waste management alternatives. There is a general need for longer term operating data on plants to determine any by-product emissions and verify energy efficiency claims. Also, with the appropriate caveats, data from facilities outside North America (e.g., in Europe and Japan), may be useful for filling gaps in the North America dataset or for comparison purposes if adjusted appropriately.

Additional research that could be done in the near term to advance the understanding of conversion technologies might include examining sensitivities and “break-even” points relative to cost and environmental aspects for key parameters such as:

- Feedstock composition (e.g., high vs. low BTU value feedstock)
- Plant energy conversion efficiency
- Recovery of materials for recycling (for MSW technologies)
- Beneficial offsets for different end product alternatives
- Distance to market for liquid fuels
- Market prices for energy products
- Market prices for recyclable and other byproduct streams.

The costs considered in this study were scarce (i.e., one data point for gasification, three data points for pyrolysis, and one data point for AD) and based on facilities that are not operating at a commercial stage. Therefore, there is inherent uncertainty in these data. For example, at the waste processing cost estimated for pyrolysis of plastics (approximately $50/ton of plastics) full-scale commercial plants should be fairly common in areas with high-cost landfill disposal.

For AD, we assumed the facilities would be stand-alone and not excess wastewater treatment digestor capacity. This assumption was made to simplify the cost and life cycle environmental assessments. However, it is expected that AD economics would be favorable for utilizing unused wastewater treatment capacity. For example, according to CalRecycle (2009), the estimates for the state of California indicate that if 75 percent of the capacity comes from existing wastewater treatment facilities and 25 percent from stand-alone facilities, the total annual costs are almost six times higher than when all the capacity comes from existing facilities.

Information about the financing mechanisms proposed or in place for the facilities identified in this report was not collected. Information such as existing or planned government subsidies and private sector off-take agreements, in addition to the net cost estimates provided in this study, would give a better picture of the financial viability of these technologies.

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Attachment A: LCA Scope, Data, and Key Assumptions

For the LCA, we adopted the methodologies used to develop life cycle inventories (LCIs) as part of a life cycle assessment (LCA). LCA is a technique for assessing the environmental aspects and potential impacts of a system from raw materials acquisition through production, use, and disposal. According to the internationally accepted ISO 14040 standard, conducting an LCA includes compiling an inventory (called an LCI – life cycle inventory) of relevant inputs and outputs of a system, evaluating the potential environmental and health impacts of those inputs and outputs (called an LCIA – life cycle impact assessment), and interpreting the results in relation to the objectives of the study. In this study, we developed high-level[11] LCIs aiming to identify and evaluate the general environmental performance and cost of the conversion technologies and to compare them to a reference waste management option (landfill).

A.1 Goals

The overall goal of the analysis is to estimate the impacts that MSW-based conversion technologies have on the environment and public health. In general, the analysis will seek to quantify the life cycle environmental burdens/benefits of conversion technologies and to compare these burdens/benefits to the baseline practice of landfill disposal.

The goal of the LCA is not necessarily to make definitive conclusions about conversion technologies or the environmental preference of conversion technologies compared to the existing landfill base case. Rather, the goal is to better understand the potential environmental benefits that may result from the commercialization of conversion technologies, the tradeoffs of employing conversion technologies as alternatives to existing MSW management practices, and the variables that influence the potential environmental impacts of conversion technologies.

A. 2 Scope and Boundaries

Since pyrolysis, gasification, and AD have different functional units with respect to the type of feedstock accepted, we did not directly compare the three systems. The function of the gasification technology system is to transform the mixed waste fraction of non-recycled waste (i.e., residual waste after recycling and composting) into energy and useful products. The functional unit is then a mass unit (e.g., a ton of MSW) of mixed waste. The pyrolysis technology system manages plastic waste. Therefore, the functional unit is a mass unit of plastics waste (e.g., a ton of plastics). AD accepts organics, mostly food waste, so the functional unit is then a mass unit of organic waste (e.g., a ton of organics).

Figure A-1 illustrates the system boundaries defined for a conversion technology (CT) in this assessment. In the figure, the boundaries include not only the conversion technology and other MSW management operations, but also the processes that supply inputs to those operations, such as fuels, electricity, and materials production. Likewise, any useful energy or materials

[11] The data used for this assessment were provided by industry vendors and were not independently validated. In addition, the datasets used to characterize the technologies vary in the level of detail and the number of values obtained for particular input parameters, with only one value obtained for certain parameters.

produced from the conversion technology system are included in the study boundaries as offsets. An offset is the displacement of energy or materials produced from primary (virgin) resources that result from using secondary (recycled) energy or materials.

RTI used a gate-to-grave approach for this assessment and assumed that all waste is fed to the conversion technologies after collection and separation for recycling or composting. Some technologies will require additional screening of the feedstock prior to the conversion process and this is included as part of the conversion technology subsystem. Therefore, the boundaries of this assessment were defined by the red box in **Figure A-1**.

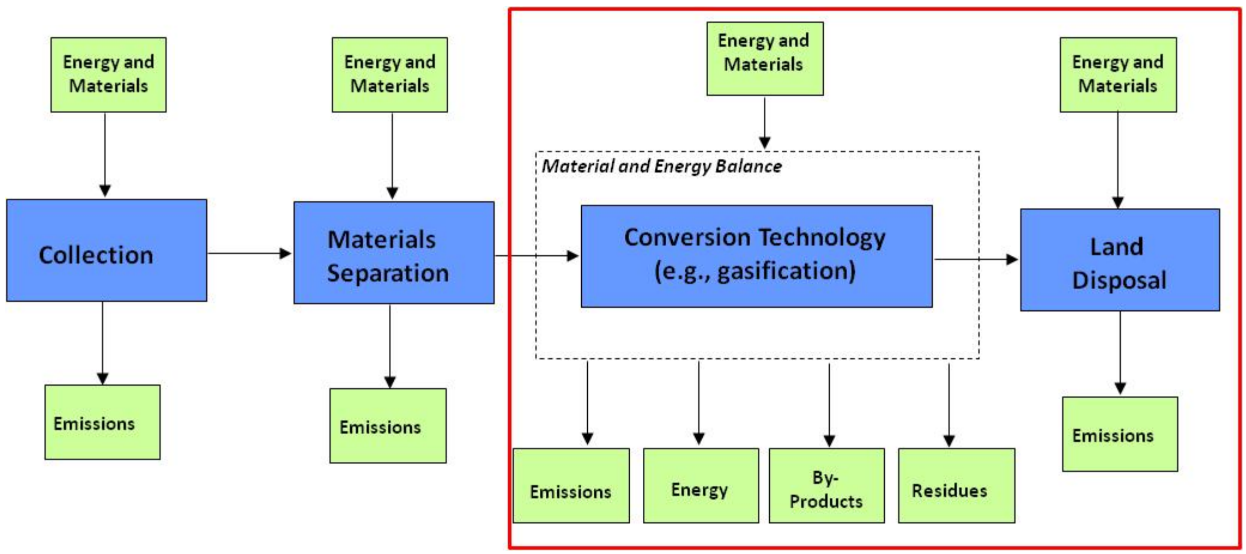

Figure A-1. General Life Cycle Boundaries for a Conversion Technology System.

Once the specific conversion technology designs were identified based on the technical evaluation of technology vendors, detailed process descriptions and process flow diagrams were prepared to identify mass flows, energy consumption, environmental releases, and other significant waste production and resource utilization parameters. An important aspect of this step was identifying the key aspects (for example, facility construction and operation parameters) of each process that needed to be considered and ensuring that all conversion technology systems were defined in a consistent manner. For example, if one conversion technology system included the production of materials used for pollution control, then all conversion technology systems should include this aspect.

In comparing conversion technologies to existing landfill disposal practices, we needed to have consistent data for each burden (for example, dioxin/furan emissions) across all unit processes in the waste management system. Therefore, if data for any given burden was not consistently available across all processes included in the system, then the burden was not included in the comparative results of conversion technologies to existing management practices. However, we did consider all burdens in this report when describing specific conversion technologies (**Sections 2-4**). In general, the main categories of inputs and outputs that are reported for each conversion technology system are consistent with those reported in the MSW DST. These include annual estimates for energy consumption, air emissions, water pollutants, and solid waste. In deciding upon which LCI burdens to present in this report, we chose energy and greenhouse gas (GHG) emissions since the input data used to estimate these results were consistently available for the various processes included in the LCIs.

A.3 LCA Methodology, Assumptions, and Modules for Waste Conversion Technologies

As part of the LCA, data was collected to quantify the relevant inputs and outputs for each conversion technology system. We collected, reviewed, and compiled data based on the conversion technology system boundaries (**Figure A-1**). We worked with the internal and external contacts to identify available data for each of the conversion technologies. Data were collected from the following sources:

- Technology vendors.
- Publicly available literature.
- Federal reports.
- State and municipal governments.
- Industry reports.
- Trade associations.
- Waste collection, processing, and disposal facility records and reports.

The scope and boundaries for each major conversion technology category are based on the technology class definitions and vendor-specific process flow diagrams presented in **Sections 2-4** of this report as well as other information collected from the literature. Each process flow diagram shows the major process steps that occur in processing and converting waste input. In addition, the diagrams show the main material and energy inputs and outputs for each conversion technology.

As shown by the process flow diagrams, the processes for which data are presented are not cradle-to-grave, but rather gate-to-gate. This is because the conversion technologies by themselves are just one process step within the system. Only after all of the pieces of life cycle inventory data from each process step within the system boundaries are assembled can the inventory module for each conversion technology be completed. These inventory modules rely on the material and energy data provided by the vendors and/or obtained from the literature as a starting point and then add the inventory information for upstream and downstream steps. In general, the construction of the LCA module for each conversion technology is depicted as follows:

LC input/output burdens – Offsets = Net LCI Coefficients

For example, gasification may use natural gas as a supplemental fuel. The amount of natural gas consumed for a given tonnage of waste processed is calculated in the material and energy model. This amount is multiplied by the environmental burdens associated with producing the natural gas and added to the inventory for the technology. Similarly, the gasification process generates some residual waste and char that is landfilled. The environmental burden associated with the transportation and landfill disposal of these residuals was added to the inventory for the technology.

Material and energy offsets are netted out of the LCI. In the case of pyrolysis, the main products are waxes and liquid fuels, each having a number of possible end uses. For this study, we assumed that it would be used as a replacement for fuel oil. The quantity of commodity oil that is produced by the process (as given by the material and energy model) is converted to an equivalent function amount of fuel oil. That amount of fuel oil offset is then multiplied by the inventory burdens associated with fuel oil production, and these burdens are netted out of the inventory for the technology.

A.3.1 Treatment of Material and Energy Recovery

Only energy recovery was included within the conversion technologies' boundaries. Some gasification vendors report material recovery from pre-processing of the mixed waste arriving at their facilities. However, because we assumed non-recycled waste would be the input feedstock, there would likely be only small amounts of available recyclables. In addition, the current test/demonstration nature of the facilities means they do not yet have contracts in place and/or data for materials recovery and available markets. For these reasons, as well as maintaining consistent treatment across the technologies, materials recycling related benefits were not included in the assessment.

For energy-related offsets, we assumed that electrical energy produced from landfill gas-to-energy and conversion technology systems displaces electrical energy produced from fossil sources. The exact mix of fossil fuels displaced is based on the U.S. average grid mix. Electrical energy is produced mainly from the gasification and AD technologies.

For the pyrolysis/cracking technologies, commodity oils/waxes are the main product. We assumed that the commodity oils/waxes displace petroleum-based crude oil.

A.3.2 Items Excluded From the LCA

A number of items have been excluded from the LCA because they are typically found to be negligible in terms of the inventory totals. These items are described below.

The energy and environmental burdens associated with the manufacture of capital equipment is not included in the life cycle profiles. This includes equipment to manufacture buildings, motor vehicles, and industrial machinery. The life cycle burdens associated with such capital equipment generally, for a ton of materials, becomes negligible when averaged over the millions of tons of product that the capital equipment manufactures compared to the burdens associated with the processing steps.

The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the calculations. For most industries, space conditioning energy is quite low compared to process energy. Energy consumed for space conditioning is usually less than 1 percent of the total energy consumption for the manufacturing process. The energy associated with research and development, sales, and administrative personnel or related activities have not been included in this analysis.

For each system evaluated, small amounts of miscellaneous materials are associated with the processes that are not included in the LCA results. Generally these materials make up less than 1 percent of the mass of raw materials for the system. For example, the use of biocides and other conditioning chemicals for cooling water are not documented and included in the inventory results, except to the extent that these materials contributed to waterborne emissions from the facilities.

A.3.3 Parameters Tracked and Reported

The main categories of LCA inputs and outputs that were tracked and reported as part of this study include annual estimates for the following:

- Energy consumption and production.
- Criteria air emissions
- Greenhouse gas emissions.
- Waterborne pollutants.
- Residual solid wastes.

Descriptions of what comprises each of these main categories are provided in the following sections.

Energy Consumption

Annual energy consumed is aggregated across process and transportation steps in the life cycle of each conversion technology module. All fuel and electrical energy units are converted to British thermal unit (BTU) values. Electricity production assumes the average U.S. conversion efficiency of fuel to electricity and accounts for transmission and distribution losses in the power lines. Therefore, the KWh value is the aggregated amount of electricity used by the system, as delivered to the various facilities in the life cycle. The BTU value accounts for the average mix of fuels (for example, coal, natural gas, hydroelectricity, nuclear) used by utilities to produce electricity in the United States.

Where energy is produced by a process and displaces the production of electricity or a fuel by a utility or the petroleum sector, respectively, such as the combustion of MSW with energy recovery, a credit is given to the extent that it displaces power generation by the utility sector or production of the fuel. For this study, we used the U.S. average electrical energy grid mix to calculate the life cycle inventory burdens associated with electrical energy consumption, as well as the credits associated with electrical energy offsets. **Figure A-2** presents the fuel mix in the U.S. average electrical energy grid (U.S. EIA, 2009).

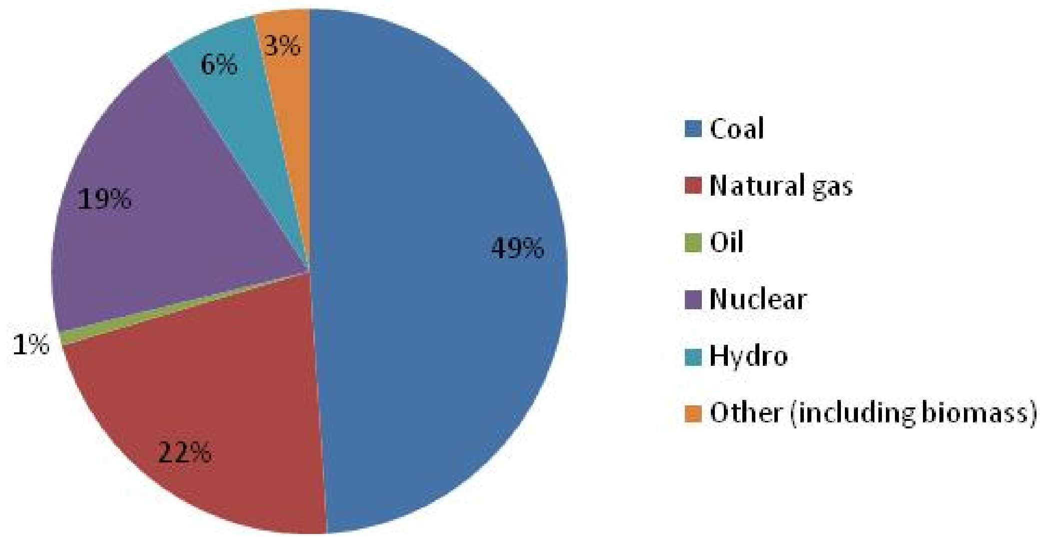

Figure A-2. U.S. Average Electrical Energy Grid Mix of Fuels (U.S. EIA, 2009).

Air Emissions

Air emissions can result from two primary sources in the life cycle: process-related activities or fuel-related activities. Process emissions are those that are emitted during a processing step, but not as a result of fuel combustion. For example, calcination of limestone to produce lime emits CO_2. The quantity of CO_2 emitted from this process would be listed under process air emissions. Fuel-related emissions are those emissions that result from the combustion of fuels. For example, the combustion of wood byproducts in a paper mill produces a fuel-related solid waste, ash. The emissions reported on the data tables in the product summaries are the quantities that reach the environment (air, water, and land) after pollution control measures have been taken.

Atmospheric emissions include substances released to the air that are regulated or classified as pollutants. Emissions are reported as pounds of pollutant per annual tonnage of waste managed. Atmospheric emissions also include CO_2 releases, which are calculated from fuel combustion data or process chemistry. CO_2 emissions are not regulated; however, we are reporting them in this study because of the growing concern about global warming. CO_2 emissions are labeled as being from either fossil or nonfossil fuels.

CO_2 released from the combustion of fossil carbon sources (for example, coal, natural gas, or petroleum) or released during the reaction of chemicals derived from these materials is classified as fossil CO_2. CO_2 released from mineral sources (for example, the calcining of limestone to lime), is also classified as fossil CO_2. CO_2 from sources other than fossil carbon sources (that is, from biomass) is classified as nonfossil carbon dioxide. Nonfossil CO_2 includes CO_2 released from the combustion of plant or animal material or released during the reaction of chemicals derived from these materials. The labeling of the CO_2 releases as either fossil or nonfossil is done to aid in the interpretation of the results. The source of CO_2 releases is an important issue in the context of the natural carbon cycle and global warming.

Waterborne Pollutants

Waterborne wastes are produced from both process activities and fuel-production activities. These are reported as pounds of pollutant per tonnage of waste managed. Similar to air emissions, the waterborne pollutants include substances released to surface water and groundwater that are regulated or classified as pollutants. The values reported are the average quantity of pollutants still present in the wastewater stream after wastewater treatment and represent discharges into receiving waters.

Air or waterborne emissions that are not regulated or reported to regulatory agencies are not reported in the inventory results presented in the material summaries. Reliable data for any such emissions would be difficult to obtain, except for a site-specific study where additional testing was authorized. Conversely, some air and waterborne emissions data that are regulated and reported may not have been included in the inventory results. The data used represent the best available from existing sources.

Solid Waste

Similar to air and water emissions, solid wastes are produced from process and fuel production activities and are reported as pounds of pollutant per tonnage of waste managed. Process solid wastes include mineral processing wastes (such as red mud from alumina manufacturing); wastewater treatment sludge; solids collected in air pollution control devices; trim or waste materials from manufacturing operations that are not recycled; and packaging materials from material suppliers.

Fuel-related solid wastes are fuel production and combustion residues, such as the ash generated by burning coal or wood.

A.4 Key Data and Assumptions Used in the Technology LCAs

Table A-1 presents key LCA assumptions for the different conversion technologies, as well as for supporting waste management activities (collection) and landfill disposal.

Table A-1. Key Assumptions Used in the LCIs.

Parameter	Assumption
General	
Waste Input	Gasification: 1 ton of mixed non-recycled waste
	Pyrolysis: 1 ton of plastics
	Anaerobic digestion (AD): 1 ton of organics
Waste Composition	Gasification: average U.S. post-recovery composition from U.S. EPA (2008)
	Pyrolysis: 100% plastics
	AD: food waste, yard waste, paper
Transportation Distances	
Conversion facility to ash landfill	30 miles one way
Gasification facility to landfill	30 miles one way
AD facility to landfill	30 miles one way
Gasification	
Basic Design	Accepts mixed waste; includes recyclables recovery; syngas as the main product
Waste Input Heating Value	12 MMBtu/ton (based on waste composition)
Assumed Offset for Energy Recovery	Solid waste to electricity: U.S. average electricity grid mix of fuels
Pyrolysis	
Basic Design	Only accepts plastics; does not include recyclables recovery; oil/wax as the main product
Waste Input Heating Value	28 MMBtu/ton (plastics only)
Assumed Offset for Energy Recovery	Fuel oil
AD	
Basic Design	Only accepts food, yard, and paper wastes; assumed biogas as the main product
Waste Input Gas Yield	3,281 ft3/ton
Assumed Offset for Energy Recovery	Solid waste to electricity: U.S. average electricity grid mix of fuels
WTE	
Basic Design	Mass burn with electricity production and metals recovery from ash (for MSW combustion only)
Plant Heat Rate	14,000 (low end) and 18,000 (high end)
Assumed Offset for Energy Recovery	U.S. average electricity grid mix of fuels
Landfill	
Basic Design	Conventional, Subtitle D Type
Time Period for Calculating Emissions	100 years
Landfill Gas Collection Efficiency	75%
Landfill Gas Management	Flare (low end) and Energy Recovery (high end)
Assumed Offset	U.S. average electricity grid mix of fuels